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CORAL REEFS AND SUBMARINE BANKS

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PART II

Fundamental postulates of the glacial-control theory.—If we now return to the consideration of the principal postulate of the glacial-control theory, it should be noted that the features appealed to in evidence of long-enduring ocean-bottom stability are not directly concerned with the deep ocean floor itself, for the ocean floor is inaccessible to geological observation; nor do they concern the geological structure of islands with elevated reefs which give a decipherable record, for nearly all of these islands seem to have had elevations and subsidences during their long history. The glacial-control theory is chiefly concerned with atolls and submarine banks, the history of which is not directly decipherable; and the features which are taken to demand long-enduring crustal stability are, as already noted, the nearly level floors and the similar and moderate depths of atoll and barrier-reef lagoons and of submarine banks, although they are all covered with unconsolidated calcareous deposits of recent deposition and unknown thickness.

In seeking to account for these well-substantiated submarine features, the glacial-control theory advances reasons for thinking that the nearly level lagoon deposits must be of small thickness and

must therefore rest on nearly level rock platforms at a moderate and fairly uniform depth in all the coral seas. It is next argued that the production of the inferred rock platforms was preceded by subaërial erosion and marine abrasion during a long preglacial period of "general crustal stability in the coral sea," whereby lofty volcanic islands were worn down to insular lowlands. Then, in view of the plausible inference that reef-making corals were killed during the glacial period, it is further supposed, as previously outlined, that the chilled and lowered ocean was free to cut away the dead reefs and to reduce the worn-down islands to flat platforms. Finally, as the ocean rose and warmed in postglacial time, the existing reefs are believed to have grown up around the platform margins, while unconsolidated calcareous deposits were strewn evenly over the platform surface; or, if reefs did not grow up, the platforms remained as submarine banks.

The ingenuity with which the successive conditions and processes are enchained is certainly admirable, but the fundamental assumptions do not seem to be fully established, and the conclusions reached are not unescapable. The links of the chain of argument must be separately examined. The plausible inference that reef-making corals were killed during the glacial period will be considered in the next two sections.

Coral reefs not destroyed during the glacial period.—It is certainly plausible to suppose that reef-building corals may have been killed by the lowering of oceanic temperatures during the glacial epochs of the glacial period, but no sufficient tests of the correctness of this supposition have been brought forward. As far as I have been able to analyze the question, the reefs were not so completely divested of protecting organisms, except along the margin of the coral zone, as to expose them and their inclosed islands to abrasion, for the consequences of such abrasion are not found in the expectable form of spur-end cliffs (*KN*, Fig. 3*b*) on the central islands of fringing or of close-set barrier reefs, as I have elsewhere pointed out;[1] hence this essential element of the glacial-control theory lacks

[1] "A Shaler Memorial Study of Coral Reefs," *Amer. Jour. Sci.*, XL (1915), 223–71; see pp. 236–46. "Problems Associated with the Study of Coral Reefs," *Sci. Monthly*, II (1916), 559–77.

support. The previously stated arguments which lead to this conclusion need not be repeated here, but additional evidence to the same end may be presented from Hawaii, Tahiti, and Murea.

Evidence from Hawaii, Tahiti, and Murea.—Let it first be noted that Hawaii, Tahiti, and Murea are three of four islands—the other is Rotuma, north of Fiji—which Daly instances as having "submarine benches so narrow as to prove the extraordinary power of fresh lavas to resist the Pleistocene breakers" (182). Rotuma I have not seen, but Gardiner's account of it[1] suggests that the narrowness or absence of an abraded bench around it may be due rather to the recency of its latest lava flows than to their resistance. Hawaii also was not reached during my voyage of 1914, but Branner's account of it[2] and the several excellent topographic sheets recently published by the United States Geological Survey of its northern and northeastern coast give good reason for thinking that the general absence of a cliff-backed bench around its shores is due to the recency of the eruptions that have covered most of its slopes with lava flows in which valleys are not yet eroded; while the occurrence of deep consequent valleys and strongly clift intervalley spur ends in the Hamakua district of the northeast coast gives equally good reason for regarding that part of the island as much older than the rest—old enough in fact to have suffered submature dissection and mature abrasion, but at a time when the island stood several hundred feet higher than now, as Branner has so well shown. By constructing longitudinal sections and cross-sections of the great valleys from the topographical maps, I have inferred that the amount of submergence since the valleys were cut down and the cliffs were cut back is some 800 feet. But whether submerged or not, the island of Hawaii ought not to be instanced in proof of the belief that the absence of spur-end cliffs on the central islands of barrier reefs elsewhere in the Pacific is due to the resistance of their lavas: to my reading Hawaii supports the other side of the

[1] J. S. Gardiner, "The Coral Reefs of Funafuti, Rotuma, and Fiji . . . . ," *Proc. Cambr. Phil. Soc.*, IX (1898), 417–503.

[2] J. C. Branner, "Notes on the Geology of the Hawaiian Islands," *Amer. Jour. Sci.*, XVI (1903), 301–16.

discussion, namely, that volcanic islands which are indented by drowned-valley embayments half a mile or a mile wide must, like northeastern Hawaii, have had strong cliffs cut in their spur ends if they were exposed to abrasion during the considerable period required for the erosion of the now drowned valleys; and as such cliffs are prevailingly absent on reef-encircled islands the islands must have been protected from abrasion—that is, their reefs must have been clothed with growing organisms of some sort—while the now drowned valleys were eroded.

Tahiti gives even stronger evidence to the same end. This island consists of a larger and a smaller volcanic cone, joined in an isthmus. The slopes of the cones are submaturely or maturely dissected by deep, steep-sided, radial valleys, the lower ends of which have been embayed by submergence after they were eroded; but the embayments are now, with few exceptions, filled with deltas which have expanded outside of their embayments so as to form a continuous alluvial belt around much of the shore line; it was this "broad belt of low land at the foot of the mountains" which Darwin properly interpreted as indicating "a long stationary period" for Tahiti. It is, however, not the radial valleys but the spur-end cliffs that are the most significant feature of Tahiti in the present connection. Agassiz gave a good account of them. Some of the cliffs rise 500 or 1,000 feet above present sea-level on the more exposed coasts; but the northwestern or leeward corner of the island is without visible cliffs for a short distance. Their origin must have been contemporaneous with the erosion of the valleys; hence the base of the cliffs and the platform that must have been abraded at a small depth below sea-level when the cliffs were cut back must be now, like the distal portion of the valleys, submerged. The depth of submergence, inferred from the cross-section of some of the larger valleys, may well be 500 or 600 feet; the lagoon, much aggraded, is naturally of less depth.

It is immaterial for the moment whether the opportunity for cliff-cutting around Tahiti was given while the ocean was chilled and lowered in the glacial period, or whether it was given while the island stood higher and was, like Reunion, reefless because a sheet of shore detritus prevented coral growth, as I believe is the more

probable explanation.[1] The lesson to be learned here is that the time which sufficed for the erosion of the steep-sided valleys of Tahiti sufficed also for the cutting of its great cliffs; hence, far from proving the power of fresh lavas to resist the breakers, Tahiti proves that, resistant as its lavas may be—and they certainly look very resistant where ledges are exposed in the cliff faces and on the valley sides—the waves of the trade-wind sea can strongly abrade the coastal slope of a volcanic island in the same period of time that is needed for the erosion of submature or mature valleys; and that the spur-end cliffs thus formed may be of such height that they will still rise hundreds of feet above sea-level after the cliff base and the platform in front of it and the valley ends between the clift spur ends are submerged hundreds of feet below sea-level. It therefore still seems to me reasonable to be guided by the conclusion elsewhere set forth that the general absence of spur-end cliffs in the central islands of close-set barrier reefs and especially in islands like Rarotonga, that have only a fringing reef, contradicts the assumption that reef-building corals were killed and that the islands that they normally protect were exposed to abrasion during the glacial period.

In order to avoid misunderstanding, let it be added that many spur ends of reef-encircled islands are nipped off in low, freshly cut bluffs, 5 to 30 feet in height, and that these low bluffs are fronted by wave-swept rock platforms of small breadth visible at low tide; hence these bluffs and platforms must be ascribed to wave work of the lagoon waters now or recently in progress at present sea-level. Further, let it be noted in passing that the subsidence inferred for Hawaii must have taken place while its gigantic young cones were in process of formation by eruption; and that a subsidence of Tahiti during its eruptive growth is also suggested, but less definitely, by its association with its more submerged neighbors. These two instances deserve consideration as antidotes to the prevailing idea that volcanic eruption is necessarily associated with upheaval. It is eminently possible, if not probable, that the reverse relation may often obtain, and still more possible that subsidence may set in shortly after eruption ceases.

[1] "Clift Islands in the Coral Seas," *Proc. Nat. Acad. Sci.*, II (1916), 284–88.

Murea, near Tahiti, may be briefly considered. Its dissection is far more advanced than that of Tahiti; its slopes are less steep, its embayments are much larger and wider; several spur ends of its northwest or leeward coast are rather strongly truncated in sloping facets resembling mature cliffs, but around most of its circuit the spurs descend gradually to sea-level; the barrier reef here is comparatively close-set. Surely, if the great cliffs of Tahiti were cut under the conditions assumed in the glacial-control theory, great cliffs should have been cut at the same time around Murea, especially on its southern and eastern sides; the absence of such cliffs indicates that the sea has not had access to the island shore, or, in other words, that the encircling reef of Murea has long protected the island from abrasion. The absence of cliffs cannot be explained under the glacial-control theory by postulating an exceptional resistance for the lavas of Murea; for if the total duration of lowered sea-level during the glacial period were long enough for small streams to deepen their valleys and for the slow processes of weathering to widen the deepened valleys to the form now seen in the drowned-valley embayments in spite of the exceptional resistance postulated for the island lavas, then the waves of the lowered sea working through the same duration of time should all the more have cut great spur-end cliffs; for there can be no question that the waves of the trade-wind sea are much more powerful agents of island sculpture than the streams of short valleys and the weather changes on the valley sides. The same statement may be made for Rarotonga in the Cook group; it is elaborately dissected by wide valleys, but its embayments are replaced by alluvial plains. Its spur ends are not clift.

The Society Islands, therefore, do not support—indeed, they strongly contradict—the consequences expectable from the glacial-control theory as to the abrasion of preglacial reefs; and I believe that they likewise give no support to, if they do not contradict, the fundamental postulate of the "long period of nearly perfect stability for the general ocean floor" on which that theory is constructed; for the depth of submergence indicated by the form of the mountain slopes that inclose the embayed valleys of these islands demands a greater submergence than the glacial-control theory provides.

Furthermore, the zoölogical evidence provided by Crampton's recent elaborate investigations is so strongly confirmatory of the subsidence which earlier investigators had inferred from similar but briefer studies that the postulate of stability for these islands in particular needs revision. Crampton's conclusion is: "The occurrence of related forms [of land snails] in Tahiti, Raiatea, and Moorea means that in former times these islands were connected by land; that the common ancestral stock ranged over the whole land mass, and that its local products differentiated into the distinct species after the process of subsidence had isolated the mountains now forming the separate islands."[1]

No truncated volcanoes are known in the coral seas.—If atolls have been formed by the processes of the glacial-control theory, then after an atoll is sufficiently uplifted and dissected an abraded volcanic platform, around the margin of which the atoll reef was built up, should become visible. Most uplifted atolls are either not raised enough or not eroded enough to reveal a foundation 40 fathoms or 240 feet beneath their reef level. In eastern Fiji, however, a number of limestone islands, that I believe were formed as atolls, have been sufficiently uplifted and dissected to reveal their volcanic platform if it ever existed. In no case is it laid bare; hence, as far as these examples go they discountenance the theory. I have given details of these islands, taken chiefly from reports by Gardiner and Agassiz, in another paper.[2] There are, on the other hand, a number of uplifted fringing and barrier reefs in Fiji, and also I believe in the New Hebrides, the Solomon Islands, the Philippines, and elsewhere, which rest, as above noted, unconformably on the previously eroded slopes of volcanic or other foundations, and in which the length of the eroded slope is so great—and I believe it may be added, the volume of erosion accomplished in shaping the slope is so large—that neither the length of the slope nor the volume of the erosion can be reasonably explained as the work of subaërial destructive processes while the sea-level was lowered only 40

[1] H. E. Crampton, "Studies in the Variation, Distribution, and Evolution of the Genus *Partula* . . . . ," *Carnegie Institution of Washington*, 1916, p. 296.

[2] "The Structure of High-Standing Atolls," *Proc. Nat. Acad. Sci.*, III (1917), 473–79.

fathoms in the glacial epochs. All such reefs appear to me to demand subsidence for their explanation; but as they all occur in the Western Pacific, and not in the central area where only atolls prevail, they do not bear directly on the atoll problem. All that can be said of such unconformable reefs and of the uplifted and dissected atolls of Fiji is that their evidence is highly favorable to Darwin's theory, and that it is in some degree irrelevant to the origin of open-ocean atolls, which are the main subject of the glacial-control theory.

As far as my reading goes only three sections have been published in which the foundation of an actual coral reef is represented as a truncated volcanic mass. One section is of the island of Mango, Fiji, as interpreted by E. C. Andrews;[1] the truncated surface is represented as covered by a now elevated coral reef into and over which later volcanic rocks are erupted; the section is reproduced as if authentic in de Margerie's translation[2] of Suess's *Antlitz der Ende;* but, as the surface of truncation is drawn below present sea-level and as the accompanying text gives no sufficient evidence of its existence, it must be regarded as hypothetical. My brief visit to the island did not enable me to examine its structure closely; but nothing that I saw gave any support to the theory of its having suffered truncation before its elevated reef was formed, nor did it appear to me that the elevated reef is older than the volcanic rocks that are associated with it. If the island really has been completely truncated, it constitutes a remarkable exception to the rule prevailing in Fiji, where the other volcanic islands have not been cut back enough to form strong shore cliffs.

A second section of a truncated volcanic island is to be found in Pirsson's account of the recent boring at Bermuda,[3] where volcanic rocks were reached at a depth of 245 feet below sea-level and penetrated to a depth of 1,278 feet. It appears to me regrettable that a single boring of this kind should be accepted as giving sufficient

[1] E. C. Andrews, "The General Geology of the Fiji Islands . . . . ," *Bull. Mus. Comp. Zoöl.*, XXXVIII (1900), 1–50.

[2] *La Face de la Terre*, III (1913), 1061.

[3] L. V. Pirsson, "Geology of Bermuda Island; the Igneous Platform," *Amer. Jour. Sci.*, XXXVIII (1914), 189–206.

ground for drawing the volcanic cone with a broadly truncated surface "cut away by the action of the sea" at the depth where igneous rocks were first encountered; almost any other form would accord as well with the recorded facts; indeed, in view of the strong variations of magnetic force on the island surface,[1] it is eminently probable that the buried volcanic surface is uneven; if so, it is also probable that the depth of 245 feet is not the minimum depth of the volcanic foundation; for if the surface is uneven it is not likely that a single boring, located without any knowledge of the understructure, would reach the culminating point.

The third example of a truncated volcanic island is Mangaia in the Cook group, which is briefly described by Marshall as having "a well-developed marine erosion surface forming the summit of the island 650 feet above sea level. An alluvial flat . . . . separates the high volcanic land from a ring of coral 125 feet above sea level . . . . 200 or 300 yards from the volcanic land."[2] This example, being visible, is better attested than the other two. It would seem to represent a volcanic cone that was completely truncated by abrasion before any reef defended it, and then elevated; but the barrier-reef ring now surrounding it may well have been formed during a later depression before a later elevation.

It is not without careful consideration that I have been constrained to reject the assumption that reef-building organisms were so completely killed during the glacial period as to leave the reefs an easy prey to the waves. The assumption is, as already noted, certainly a plausible one at first hearing, and it merits careful examination; but as the result of the best examination that I have been able to devise it proves to be erroneous. Thus a problem is laid before zoölogists: If coral reefs are today limited by temperature conditions and if the ocean were significantly cooled during the glacial period, why were not the reef-building organisms then killed? Perhaps the organisms were killed and the reefs were cut away on islands near the borders of the coral zone, as will be

[1] J. F. Cole, "Magnetic Declination and Latitude in the Bermudas," *Terrestr. Magnetism*, XIII (1908), 49–56.

[2] P. Marshall, "Coral Reefs of the Cook and Society Islands," *Proc. Austral. Assoc. Adv. Sci.*, XIII, 1912, 140–45.

further considered later. Perhaps the corals were very generally killed, but the nullipores were not; if so, the nullipores, although unable to construct a reef alone, might cover and protect the exposed flanks of an already constructed reef for a geologically brief epoch until the corals could again establish themselves upon it.

The floors of atoll lagoons.—Whatever solution the question of the survival of reef-building corals during the glacial period may eventually receive, it may be set aside for the present and return may be made to the main facts upon which the glacial-control theory is built, with the question, Is it really impossible to explain the smoothness of atoll-lagoon floors and of submarine banks without prolonged abrasion of still-standing islands? This seems to me no impossibility. Those smooth surfaces are not the result of abrasion, even if an abraded surface exists beneath them; they are the result of the even distribution of organic sediments by agencies now in operation, whatever the shape of the foundation that the sediments rest upon, as will appear from the following consideration.

As to atolls, it is true that the waters of their lagoons are generally placid, but it is also true that at times of storm they are agitated sufficiently to become turbid by stirring up the bottom sediments. Gardiner's testimony on this point, based on observations in the Maldives, is important:

> It is only in a few protected situations, where the depth is as great as 40 fathoms or more, that the lagoon bottom appears not to be churned up by the currents and waves. In heavy weather the lagoon water is almost milky, and floating surface nets [for zoölogical collecting?] are almost useless on account of the enormous amount of mud in suspension. The total amount of mud that passes out of the lagoon in the water is enormous.[1]

Hence I cannot accept Daly's statements that "the lagoon floor . . . . is little or not at all disturbed by any waves or currents generated in the lagoon itself," and that "the filling and smoothing out of the hypothetical 'moat'" about a subsiding island is little aided by the mud from the reef. "The coarser detritus" washed in from the reef flat often does "form a well-defined terrace slowly

[1] J. S. Gardiner, "The Origin of Coral Reefs . . . . ," *Amer. Jour. Sci.*, XVI (1903), 203–13; see p. 210.

growing inward from the reef," as may be seen in many lagoons, for example, those of Tahiti and Raiatea in the Society Islands. Furthermore, as a large quantity of muddy sediment is formed on the reef flat by disintegrating agencies, organic and inorganic, acting on the blocks and scraps of coral rock washed in from the exterior reef face, and as the interior terrace of white granular detritus is free from fine silt, it follows that an important share of fine detritus from the reef must reach the lagoon floor; and this reef silt, as well as the fine organic sediments formed on the lagoon floor or in the lagoon waters, is distributed by the waves and currents therein generated, as Gardiner states.

Darwin had earlier reached a fair understanding of this problem: "The greater part of the bottom in most lagoons is formed of sediments; large spaces have exactly the same depth, or the depth varies so insensibly that it is evident that no other means, excepting aqueous deposition, could have levelled the surface so equally" (26). In my own limited experience I saw the waters of two barrier-reef lagoons rolling in heavy waves under strong winds—once in Fiji, once in the broad lagoon of the Great Barrier reef off the Queensland coast—and on both occasions the water was gray with suspended sediments. It seems evident that under such conditions the finer sediments of lagoon floors will be lifted chiefly from the shallower parts and will settle in about the same amount everywhere; and the continuation of such changes will tend to produce and maintain a fairly smooth surface of sedimentation, such as actually exists.

Another view has been announced. After assigning a small value to the general distribution of lagoon sediments by the waves of gales and storms, and a large value to the distribution of sediments by currents driven under steady winds, Daly has recently reached the conclusion that lagoon floors thus aggraded during subsidence should not be level, but should be deeper to windward and shallower to leeward; then, on examining charts of atolls and verifying the general levelness of lagoon floors, he concludes that subsidence has not taken place, but that the reefs have grown up and the lagoons have been evenly aggraded in postglacial time because their sediments have been deposited on smoothly abraded

still-standing platforms.[1] The conclusion does not seem tenable because the smooth floors of a good number of medium-sized atoll lagoons in the trade-wind belts have moderate depths, such as 20 or 25 fathoms, and must therefore, even under the glacial-control theory, have been aggraded by 15 or 20 fathoms if their abraded platform lies at a depth of 40 fathoms. Moreover, the fact, more fully stated in the next section, that small atolls have on the average shallower lagoons than large atolls proves that a good share of their sediments is washed in from their inclosing reefs. If aggradation by material thus partly supplied from the margin, partly from locally formed organic detritus, and distributed by trade-wind currents in the lagoons ought to produce a slanting surface of deposition, these lagoon floors should not be level; their levelness therefore contradicts the supposed necessity of slanting aggradation and confirms the theory of equable distribution and even aggradation by the lagoon waters. Hence it may be concluded that lagoon floors tend to become and to remain nearly level, whatever form the foundation of their inclosing reefs may have had, and whatever the thickness of their sediments may be; and, conversely, that the form of a lagoon floor gives no indication of the form of its buried foundation. I am therefore constrained to think that the general levelness of atoll-lagoon floors is no sufficient reason for the existence of a level rock platform at a moderate depth beneath.

The depth of lagoon floors.—If, then, the smoothness of lagoon floors is no sufficient proof of the existence of a smoothly abraded rock floor beneath them, we may next inquire as to evidence for the existence of such a rock floor that is found in the similar depth of atoll lagoons and of submarine banks. The depths are not all alike. As to atolls, Daly has shown that on the average the smaller ones are the shallower, and from this he draws the acceptable conclusion that "the smaller the platform the higher was the proportion of reef débris in the veneer, and the more rapidly has the lagoon area been shallowed" (183), and again that "the filling of the lagoon [by inwashed sediments] is in indirect proportion to

[1] R. A. Daly, "A New Test of the Subsidence Theory of Coral Reefs," *Proc. Nat. Acad. Sci.*, II (1916), 664–70.

the width of the platform [atoll]" (192);[1] but as this conclusion would follow equally well whether the reefs have grown up with the rising ocean around a still standing abraded platform, or in a stationary ocean around a sinking and submountainous foundation, no ground for choice between the two theories under discussion is here provided.

A closer scrutiny of the figures, however, reveals considerable differences of lagoon depth in atolls of about the same size, and this seems more consistent with the variable conditions offered by the theory of intermittent subsidence than with the strictly uniform conditions assumed under the theory of glacial control. For example, among 12 atolls listed in Daly's table as from 21 to 30 kilometers in diameter, the smallest value of maximum lagoon depth is little more than half the value of the largest maximum; and this smallest maximum is in an atoll the diameter of which is greater than the one which has the largest maximum. Ringgold atoll, in Fiji, is given as having a maximum lagoon depth that is more than twice as great as the maximum depth in North Argo atoll, of the same group, though both have the same moderate diameter of 10 miles. Among wide barrier reefs the one adjoining New Caledonia on the northeast has a maximum depth less than half that of the lagoon of similar breadth on the northwest of Viti Levu, in Fiji. Moreover, some lagoons reach unusual depths. In the large lagoon, just mentioned, northwest of Viti Levu, the largest island of the Fiji group, the lagoon deepens and the inclosing reef is submerged, as the distance from the island increases, in such a way as strongly to suggest recent tilting; a sounding of 59 fathoms is the maximum there recorded, but the outermost part of the lagoon has not been measured. The large lagoon of the Exploring Isles in the eastern part of Fiji deepens eastward to 80 or 90 fathoms, and this again suggests tilting, as Agassiz noted. Cases of this kind are as significant as they are exceptional. But it should be noted that many atolls of the Central Pacific are, according to the latest charts of all sources available in the Hydrographic Office at Washington, incompletely surveyed; further exploration is needed

[1] The misprint "direct" in the original article is here changed to "indirect" with the author's approval.

before their testimony can be used. In any case, even in atolls of similar diameter, the depths of the lagoons vary so much that they alone cannot be taken as proving that the atoll reefs have been built up with the rise of the ocean from stationary platforms of uniform depth.

The fact that the maximum depth of atoll lagoons seldom exceeds 40 fathoms does, however, suggest the existence of some control that has prevented the occurrence of greater depths; but this control may be found elsewhere than in the abrasion of platforms at a uniform depth below sea-level. For example, if the subsidence of an atoll or a barrier-reef island is relatively rapid, the reef will be somewhat submerged, the inwash of detritus from the reef will be active, and the increase of lagoon depth will be retarded; if subsidence is, on the other hand, relatively slow, the reef will be maintained at sea-level and will broaden its surface, sand islands will be formed along its edge, and inwash of detritus into the lagoon will practically cease; hence, in spite of slow subsidence the lagoon will not be rapidly shoaled. Thus, unless subsidence be unusually rapid, there appears to be a series of spontaneous reactions which tend to prevent lagoon depths from varying by large measures. Wherever unusually rapid subsidence occurs, the atoll would be drowned and converted into a submarine bank. The scarcity of such banks in the Pacific, as far as it is now explored, suggests very strongly that subsidence has rarely been unusually rapid; and slow, equable, or intermittent subsidence, being a near approach to long-continued stability, does not appear to be particularly incredible. But, however that may be, the known depths of atoll lagoons can be explained as well by the theory of intermittent subsidence as by the glacial-control theory. The depth of submarine banks will be discussed in a later section.

The volume of existing reefs.—The glacial-control theory suggests that a very uniform upgrowth of reefs should take place in the uniformly rising postglacial ocean, and that all existing reefs should therefore be of similar surface breadth and of similar volume. Daly finds this to be the case; he says that "the widths as well as the heights of the existing barrier and atoll reefs are of the proper

size, if these calcareous rims originated on the platforms in post-glacial time" (219). As to the height of reefs we know little, because the depth of their base is undetermined. Nothing is gained by assuming their base to be 40 or 50 fathoms below present sea-level, for the resulting uniformity of height has no verification. However that may be, the visible differences in the height of reefs above their lagoon floors and the breadth of reefs at sea-level seem to me too great to support the above conclusion. Yap, in the western part of the Caroline group, Western Pacific, and Rodriguez, in the Southern Indian Ocean, have broad reef plains, a mile or more in width, attached to the central islands; that of Rodriguez is 4 miles wide on the southwest side of the island. Borabora, in the Society Islands, has a barrier reef and reef flat half a mile or a mile wide, and a comparatively shallow lagoon; Mbengha, in Fiji, has a reef and reef flat of similar width around the southern side of its lagoon; the reef around Nairai, in central Fiji, is a half or a quarter of a mile wide; Budd reef, in northeastern Fiji, is narrow, generally less than a quarter-mile across, and its lagoon is 46 fathoms deep; yet near by is the long and irregular Ringgold atoll, in which the reef is half a mile or a mile wide, though the lagoon is of similar depth to that of Budd reef; Tahiti has a narrower reef, often discontinuous; Fauro, in the Solomon Islands, is fringed with a narrow sea-level reef and surrounded by a submerged bank, 70 fathoms deep in places, on which a very imperfect reef rim is found; Palawan, the southernmost member of the Philippines, is elaborately embayed along its western coast, where the headlands are neither clift nor fringed with sea-level reefs, but are fronted by a broad submerged platform, varying in depth along its length with maximum of 60 fathoms. The Marquesas Islands, nearer the equator than the numerous Paumotu atolls, have no sea-level reefs; their headlands are strongly clift, and a submerged bank extends around them. Various submarine banks have well-defined reef rims that fail to reach the surface, or that rise very discontinuously to the surface, as will be specified below; and some submarine banks are flat and rimless. Differences of these kinds in reef volume are more consistent with the unlike conditions introduced by intermittent subsidence, varying as to rate, amount, place, and

date, than with the uniform conditions demanded by the glacial-control theory.

The exterior profile of coral reefs.—There is another feature of coral reefs to which Vaughan has called attention as indicating the existence of a submerged platform previous to, and independent of, the formation of the present reefs; this is the continuation of the shallow lagoon floor, not only where it is inclosed by a reef, but also through uninclosed sectors of its area where a marginal reef is wanting. A good number of examples of this kind are known in Fiji; but it is significant that the breach in the reef is in practically all cases on the leeward side. It is further significant that the

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resulting from aggradation by the transporting

the ocean waters with respect to present ocean-level;

as small insular "shelves" of rapid development with

to the present level of the ocean and therefore as correspond-

ing to great continental shelves of long-continued development with respect to the average relation of land and sea through modern geological periods. The change of slope outside of a continuous reef will be first considered.

Darwin was, I believe, the first to suggest this view as to the origin of the exterior profile of coral reefs in his account of Keeling atoll. "As the external slope of the reef is the same round the whole of the atoll and round many other atolls, the angle of inclination must result from an adaptation between the growing powers of the coral and the force of the breakers and their action on the loose sediments" (74); and he later added, "Considering the manner in which the beds of clean coral . . . . graduated into a sandy slope, it appears very probable that the depth at which reef-

building polypifers can exist is partly determined by the extent of inclined surface which the currents of the sea and the recoiling waves have the power to keep free from sediments" (84), thus foreshadowing a view that is now generally accepted.

A good number of other observers have interpreted the gradual slope and the steep pitch outside of a reef in the same way. Thus we read in the "Challenger" report regarding the reef at Tahiti, "The whole of the space from the edge of the reef to a depth of 35 fathoms was covered with a most luxuriant growth of corals, with the exception of one or two small spaces where there was white coral sand"; the steeper pitch to greater depths was covered by coral blocks, "which have been torn away from the ledge between the edge of the reef and 35 fathoms during storms, or by overhanging masses which have fallen by their own weight. In this way a talus has been formed on which the corals living down to 35 fathoms have found a foundation on which to build further seawards, for this [upper] slope is the great growing surface of the reef."[1] It may be noted that the depth here given for abundant living corals is unusually great, and that Agassiz nearly thirty years later found a smaller proportion of growing corals and a larger proportion of dead corals, coral fragments, and coral sand on the same slope; hence the population of the slope presumably varies in relation to the master-storms of decades and centuries. But the important matter to note here in the present connection is that the outer slope of the reef, like the reef itself and the prograded "belt of low land at the foot of the mountains" of Tahiti, represents an adjustment of aggrading processes and aggraded forms with respect to present sea-level, by whatever changes the present relation of land and sea-level have been brought about.

Gardiner, whose studies of reef slopes are both intensive and extensive, says of the Fiji reefs, "The section outside all is nearly the same, a gentle slope to about 40 fathoms and then a sudden steep."[2]

[1] *Narrative of the Cruise of H.M.S. "Challenger,"* I, Part 2 (London, 1888), pp. 779, 781.

[2] "The Coral Reefs of Funafuti, Rotuma, and Fiji . . . . ," *Proc. Cambr. Phil. Soc.*, IX (1898), 417–503; see p. 445.

The same experienced observer later made a more specific statement regarding the Maldives:

> From the outer edge of an encircling reef flat there is generally to seaward a gradual slope to 30–50 fathoms in 200–400 yards, succeeded by the steep. . . . . This slope is essentially the growing area, being covered almost completely by living organisms. . . . . The outwash of detritus, largely due to undercurrents [or to general agitation by wave and current action, with the result that the finer sediments are chased about until they finally settle in deep water outside the reef where they will not be again disturbed ?], causes a raining down of coral masses and sand over the edge of the steep, carrying it out and allowing the extension of the whole outer side as a fairy ring.[1]

The growth of a reef outward, like a fairy ring, is again mentioned by the same author in his elaborate report on the Maldives.[2] A later statement by the same author is, "The steep . . . . is built up by masses of coral rock from the reef above, its angle representing that at which such material comes to rest in sea-water."[3] It is interesting to add that the change of slope on the exterior of a reef occurs at the same depth as that at which, according to Daly, "the charts of the world show the break of slope" (199) on continental shelves.

Lagoon floors of discontinuous reefs.—As to the free border of an uninclosed lagoon-floor sector, where the inclosing reef is wanting as above mentioned: It is easy to conceive that the lagoon floor there represents a more or less aggraded portion of a pre-existent platform, elsewhere inclosed by a superposed reef; and it is not difficult to explain the origin of the platform by abrasion according to the glacial-control theory as stated by Daly, or to leave it unspecified, except to say with Vaughan that it is independent of the reefs which are growing upon it. But it is also easy to conceive that the lagoon floor of today is the more or less aggraded lagoon floor of earlier days; that the lagoon floor of earlier days may have been deepened during times of rapid subsidence which caused the

[1] "The Origin of Coral Reefs . . . . ," *Amer. Jour. Sci.*, XVI (1903), 203–13; see p. 211.

[2] *The Fauna and Geography of the Maldive and Laccadive Archipelagoes* (Cambridge), I (1903); II (1906); see I, 175, 182, 183, 317.

[3] "The Indian Ocean," *Geogr. Jour.*, XXVIII (1906), 313–32, 454–55; see p. 455. Also "Submarine Slopes," *ibid.*, XLV (1915), 202–19.

upgrowth of a narrow reef, or shoaled during stationary periods and periods of slow subsidence when the reef was broadened; and that the shoaling may have gone so far as to convert a narrow young reef and a deep lagoon into a mature reef plain,[1] if subsidence were long enough in abeyance. It is furthermore easily conceivable that prevalent subsidence may have been for a time neutralized in a phase of no submergence, while the ocean-level was falling as a glacial epoch came on, and then accelerated for a time in a phase of rapid submergence while the ocean-level was rising as a glacial epoch passed off; that a mature reef plain, formed during the neutralized phase of no submergence as a glacial epoch came on, might not be completely rimmed around by a new reef which grew up during the following phase of accelerated submergence as the glacial epoch passed off; and that in such case a failure of growth might reasonably enough take place on the border of the leeward sector of the reef plain, where the quantity of fine sediment shifted about by the waves might very likely prevent or retard coral growth. All of these mental schemes—mere figments of the imagination—are, as is said above, easily conceived by anyone who cares deliberately to consider the coral-reef problem; the difficulty in the problem lies elsewhere, namely, in the discovery of tests by which one of the schemes may be shown to represent better than any other the processes of the invisible past and thus to offer the best explanation for the invisible as well as the visible structures of the present.

The best explanation that I have been able to reach is as follows. First, regarding the exterior profile of continuous reefs: In view of the evidence already given, from which it appears that the production of platforms by abrasion during the glacial period is improbable if not impossible, and in view of the fair accordance between the depths at the outer margin of the uninclosed sector of a lagoon floor and the depth on the outer face of a reef where the change takes place from a gentle slope to a steep pitch, I am persuaded that the change of slope at 40 fathoms is not an inheritance from a time when that part of the reef lay at or close to the surface of the ocean, but, as already stated, a consequence of adjustment between

[1] "The Great Barrier Reef of Australia," *Amer. Jour. Sci.*, XLIV (1917), 339–50; see p. 346.

the detritus to be transported and the agents of transportation with respect to present sea-level. Like the reef itself, the two elements of its exterior profile—namely, the gentler slope down to 40 fathoms and the steeper pitch below—have been brought by organic growth and by inorganic processes into a normal relation to sea-level. Secondly, regarding the free border of an uninclosed lagoon-floor sector of atolls and barrier reefs: In view of the alternate retardation and acceleration of submergence by the combination of prevalent subsidence with the periodic changes of ocean-level during the glacial period—for this is, in my mind, the chief value of the glacial-control theory—I am strongly inclined to regard any "platforms" that may exist, now more or less aggraded, beneath incompletely or completely inclosed lagoon floors as nothing more than the surface of earlier reefs normally broadened while submergence was so slow that narrow reefs were transformed into mature reef plains. Thus interpreted the present reefs are merely new, still young, and relatively narrow growths above their mature predecessors; narrow, because they have been developed while submergence has been accelerated. This inclination of opinion has been strengthened by an examination of charts of submarine banks both within and without the coral seas, and that aspect of the problem must next be examined.

Let it be noted, however, that if the explanation above suggested for the change in the exterior slope of a reef at 40 fathoms depth be correct, then Daly's conclusion that "the present atoll, barrier, and fringing reefs . . . . have been developed nearly or quite in the same interval of time" cannot be supported by the agreement of "their sectional areas and their volumes, as measured, in each case, above the break of slope at the platform on which the crowning reef stands" (233). A further conclusion is also vitiated, namely, that inasmuch as "the surface outcrops and volumes of the greater barrier and atoll reefs, measured from the levels of the lagoon floors, are respectively nearly equivalent in the Pacific and Indian oceans," therefore "the earth's crust must have sunk at a nearly uniform rate throughout the enormous area described . . . . if these reefs were formed by subsidence" (233, 234).

Neither the break of the exterior slope nor the level of the lagoon floor of existing reefs is, as far as I can make out, the record of a former lower sea-level: both appear to have been brought into relation with present sea-level by processes now acting. It certainly seems as reasonable to explain the exterior profile of coral reefs in this way as to explain "the break of slope on the [continental] shelves . . . . near the 40-fathom line" as a result of wave and current action at the present stand of the ocean surface, and therefore since the present stand was assumed.

[*To be continued*]

PERMO-CARBONIFEROUS GLACIAL DEPOSITS OF SOUTH AMERICA

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INTRODUCTION

The proofs of tremendous glaciation at the end of the Carboniferous have been given in great detail from South Africa and Australia and less fully from India; but comparatively little has been reported regarding Permo-Carboniferous glaciation in South America. Having seen something of the tillites and glaciated rock surfaces of typical localities in the first three regions, it seemed desirable to visit the less-known glacial deposits of South America. During the past summer this has been accomplished, and it is proposed to give in this paper a brief account of what was observed.

The probability that certain Carboniferous or Permian bowlder conglomerates with a matrix of shale in southern Brazil were of glacial origin was recognized by Orville Derby as early as 1888;[1] but no striated stones were found, and the evidence seemed scarcely sufficient to establish the point. In 1907 and 1908 I. C. White and David White made it almost certain that the widespread bowlder conglomerates were glacial, the latter showing that the accompanying flora, as collected during I. C. White's examination of the coal deposits of southern Brazil, was identical with floras in a similar relation in South Africa and India.[2] Still the final proof, the finding of striated stones, was lacking.

In 1908 J. B. Woodworth studied the southern Brazilian tillites, finding striated stones plentiful and making their glacial origin absolutely certain. His report on the field work accomplished, with

[1] Orville Derby, "Spuren einer carbonischen Eiszeit in Süd Amerika," *Neues Jahrb. für Min.*, etc., Band II (1888), 175.

[2] David White, "Permo-Carboniferous Climatic Changes in South America," *Jour. Geol.*, XV (1907), 615–33; and I. C. White, in his *Relatorio Final on the Brazilian Coal Fields*, 1908, pp. 11–119.

the aid of two young Brazilian geologists, Eusebio Oliviera and Juvenal Pacheca, is admirable and has served as guide in a portion of my own work.[1] In the following year H. Bross confirmed his conclusions, finding striated stones near Itararé.[2]

Up to 1911 Permo-Carboniferous tillite had been reported from southern Brazil only; but in that year T. G. Halle described tillite of the same age from the Falkland Islands, which may be looked on as belonging to the South American region.[3] In 1912 tillite with polished and striated stones, including bowlders up to 1.5 meters in diameter, was described by C. Guillemain, from Uruguay;[4] and in 1913 J. Keidel announced the finding of tillite of this age in southern and western Argentina in a paper read before the Twelfth Geological Congress in Toronto; while in 1916 he gave an excellent and full account of the tillite at Sierra de la Ventana in southern Argentina.[5]

From this outline of the literature on the Permo-Carboniferous glaciation in South America it will be seen that our knowledge of the distribution of the tillite is rapidly growing, extending now to three countries, and that this glacial formation is widely spread in southern Brazil and perhaps also in Argentina. In Brazil the excellent field work of Oliviera and Pacheca is constantly extending the known area of glaciation, so that in this respect South America may soon rival South Africa and Australia and surpass India.

It was planned to visit localities for tillite in several parts of Brazil and at Sierra de la Ventana in Argentina, and these plans were carried out successfully, largely through the help and advice of Pacheca in São Paulo and of Keidel at Buenos Aires. I am specially indebted to Dr. Pacheca, who has mapped the tillite in detail in the state of São Paulo, and who showed me a number of

[1] J. B. Woodworth, *Bull. Mus. Comp. Zoöl., Harvard*, LVI, No. 1, Geol. Series, X. *Geol. Exped. to Brazil and Chile.*

[2] H. Bross, "Glacial Spuren in Parana," *Cent. Bl. für Min.*, etc., 1909, pp. 558–61.

[3] T. G. Halle, *Geol. Mag.*, N.S., V, 264–65; also *Bull. Geol. Inst., Univ. Uppsala*, XI, 144–56.

[4] C. Guillemain, *Neues Jahrb. für Min.*, etc., Beil. Band XXXIII, 208–64.

[5] J. Keidel, *Comptes Rendus*, pp. 676–80; also in *La Geologia de las Sierras de la Provincia de Buenos Ayres*, Tomo XI, No. 3, *Anales del Ministerio de Agricultura of the Argentine Republic*, 1916.

typical outcrops in the field. Through his courtesy and kindness I had an admirable introduction to the Paleozoic bowlder clays of Brazil.

TILLITES IN THE STATE OF S˜O PAULO

In tropical Brazil, with its moist, hot climate, weathering goes to great depths, and even in the southern parts of the country, where the climate is warm temperate, the products of decay mantle most of the surface, so that fresh outcrops of rock are seldom to be found under natural conditions. On this account the most satisfactory points for geological work are cuttings along the railways or depressions where roads ascend hills and the wheels of vehicles have worn their way downward. To an observer fresh from parts of North America where the Pleistocene glaciation has left clean surfaces of almost unchanged rock this is most disconcerting, and it takes a little time to adjust one's self to the new conditions. The working out of field relations is greatly hampered by the products of weathering, which usually hide even the weathered rock and may accumulate to considerable depths on slopes and in valleys.

Under Dr. Pacheca's guidance a number of railway and road sections were visited to the north of the city of São Paulo, the first region being near the thriving city of Campinas. In railway cuttings two or three kilometers from the city, tillite rests upon gneiss, probably of Archean age, two mounds of the gneiss rising with rounded forms suggesting *roches moutonnées;* but unfortunately weathering has gone so far at the contact as to destroy any smoothed or striated surface that may have existed in the beginning. According to Dr. Pacheca this is almost the only example known in Brazil of tillite resting on what must have been a scoured surface of solid rock.

The tillite is weathered and scarcely harder than certain Pleistocene tills, though its yellow or red or chocolate-brown color is unlike the customary bluish gray of North American bowlder clay. Striated stones were not found here, though the general appearance of the rock was that of tillite, some of the more resistant stones inclosed in it, such as quartzite and granite, still showing subangular forms and smoothed surfaces. Overlying the tillite are shaly or sandy beds, distinctly stratified and including some-

times a thin layer of conglomerate, the series being closely related to the tillite and sometimes interstratified with it, as in many sections of Pleistocene glacial deposits.

The next point visited was near Capivary, reached by a narrow-gauge railway from Campinas, where a delightful walk of 18 kilometers disclosed excellent sections of tillite containing typically shaped and sometimes striated stones (Fig. 1) including

FIG. 1.—From Capivary, São Paulo, Brazil

bowlders of sandstone, quartzite, conglomerate, and granite occasionally reaching a diameter of one meter. The coarse conglomerate forming some bowlders quite suggests the Huronian tillite of Cobalt, Ontario, and their source in Brazil is unknown. The tillite has a thickness of three or four meters and rests on soft, stratified sandstone or sandy shale sometimes cross-bedded. In one place it is covered by a sheet of trap mostly weathered into the bright-red "terra roxa" which forms the best soil for coffee and sugar plantations.

A visit was made to a section near Villa Raffard, about four kilometers southwest of Capivary, to see some large bowlders of

the ancient conglomerate, including pebbles of jasper, another feature suggesting the Huronian rocks of Ontario. These conglomerate bowlders have also been mentioned and figured by Woodworth.

In several places shales accompanying the tillite have been thrown into folds a few meters in dimensions, either by ice-thrust at the time of glaciation or by later compression. Over the tillite in places a brown fine-grained unstratified material, pierced by worm or root holes, stands up as low cliffs and suggests an ancient loess. At one point on the railway near Capivary (kilometers 160–61) shales beneath the tillite appear to have been crumpled and then truncated, showing an unconformity between the tillite and the soft sediments beneath; and some soft sandstone bowlders in the tillite are quite like an irregularly bedded sandstone frequently found in the same position, suggesting the same relationship.

The fresh tillite is often solid enough to make vertical faces in cuttings and shows spheroidal shapes when weathering has begun. Ultimately the rain breaks it down into slippery clay, gray or yellowish or red in color, strongly suggesting a rain-crumbled Pleistocene till. Near the small station Elias Fausto, Dr. Pacheca has found tillite inclosing very large granite bowlders, one partly disclosed measuring $3 \times 3 \times 2$ meters, and looking like one of the Iowan bowlders of the Western states.

My last excursion under Dr. Pacheca's guidance was to Limeira, 50 kilometers northwest of Campinas, where a round of 21 kilometers was made over country roads giving an opportunity to see typical bowlder clay extending over many square kilometers of gently rolling country. The tillite is usually chocolate colored and in places reaches a thickness of 25 meters, while in other places it has been cut through by the stream valleys. In the steep walls of a sunken road leading out of the town plenty of well-striated stones were found, and except for the prevailing red color and a little greater hardness the outcrops reproduce perfectly the features of a region of bowlder clay in North America. It was hard to believe that the rock was as old as the Permian.

Limeira is about in latitude $22\frac{1}{2}^{\circ}$, a degree within the tropics, so that in Brazil, as in India and Australia, the ancient ice-sheet reached much nearer to the equator than any Pleistocene ice-sheet.

It is estimated by Drs. Florence and Pacheca, of the Geological Survey of the State of São Paulo, that the outcrops of tillite extend from northeast to southwest for 500 kilometers, with a width of from 50 to 100 kilometers; and it must be added that the tillite follows the gentle northwestward dip of the rocks of the region and probably extends far beneath the Triassic beds in that direction. It is evident that one is dealing with deposits formed by a great ice-sheet spread out over a peneplained surface and not with the results of mountain glaciers.

TILLITE IN STATES SOUTHWEST OF SÃO PAULO

After the admirable introduction to the study of Brazilian glacial deposits provided by the kindness of Dr. Pacheca there was little difficulty in recognizing the characteristic appearance of the tillite, and on the journey by rail from São Paulo to Montevideo in Uruguay some of the localities described by Woodworth were visited, the first just beyond the southwestern boundary of the state of São Paulo between Itararé and Sengens. In railway cuts near Sengens, Woodworth had found striated stones and large bowlders of sandstone; and a walk along the railway between the two stations proved extremely interesting.[1] Following the crooked narrow-gauge railway from Sengens northeast toward Itararé tillite is seen for eleven kilometers (from km. 241 to km. 230) resting usually on sandstone, occasionally with a hummocky surface and in one case with a suggestion of furrowing in a direction from southeast to northwest or vice versa. The sandstone is still soft, and when the tillite was deposited may have been softer, so that large blocks could easily be lifted and inclosed in the glacial materials. In addition to these masses of local rock there are quite large bowlders of shale and of granite, and a multitude of smaller stones, many of a harder sandstone than the underlying rock, and a few of quartzite. The tillite varies in thickness, sometimes reaching ten meters. Parts of it near kilometer 241 have been more or less

[1] See Woodworth's *Report*, p. 62 and Pls. xxi and xxii.

pushed and crumpled, and not far to the northeast is the great fault and escarpment mentioned by Woodworth.

The best display of tillite is about at kilometer 235, where the smaller stones are very frequently striated, more so than in any other till I have seen, whether Pleistocene or older. Many of the glaciated stones show not only "soles" but well-defined facets, as if they had been firmly held till a face was ground flat and then adjusted at another angle, resulting in another flat face. These facets sometimes come together sharply. In early days similar faceted stones from the Permo-Carboniferous tillite of India attracted attention. It would seem as if the Permo-Carboniferous ice-sheets held their imbedded stones more firmly than those of the Pleistocene. Why? Were their bases colder or was there a greater thickness of ice, giving a stronger pressure?

As may be seen from the train, tillite extends several kilometers on the route southwest; but the next stop was made at Ponta Grossa, midway across the state of Parana, where I. C. White had described outcrops of glacial conglomerate.[1] On the side of the ridge on which the town is built, cuttings, made for streets and for drainage, disclose reddish, sandy glacial deposits containing subangular stones of various kinds, a few of which were found to be striated. A fairly good section is seen also on a road leading into the country. Above the tillite there is a sheet of trap weathering into a very red soil, and beneath it sandstone followed by black shale from which Devonian fossils are reported.

A visit was made also to Serinha, 70 or 80 kilometers to the southeast, where Woodworth suspected an older tillite. Typical bowlder clay is passed between Palmeira and Nova Restingua and may be seen at Porto Amazonas. There is a rapid descent from Palmeira to Serinha, which is in a deep river-valley at the base of sandstone cliffs. The tillite here takes the form of blue or yellow shale, readily weathering to clay, containing subangular stones, chiefly sandstone, quartzite, and granite. No striated stones were found, but the bed looks like a glacial deposit. It is overlain by 200 feet of firm sandstone resembling the rock found beneath the tillite at higher levels. Beyond this fact no clue to its age was

[1] I. C. White, *Relatorio Final on the Brazilian Coal Fields*, 1908, p. 51.

observed. The whole series of rocks, including the two tills, seems to lie nearly horizontal, doubtless with a gentle dip northwestward following the regular trend of the stratification in southern Brazil. The tillite at Serinha looks no older than that described before, and may represent merely a Carboniferous forerunner of the more important glaciation to follow.

Southeast of Ponta Grossa the railway lies too far west to give opportunities of observing the glacial deposits, passing over trap-sheets, Triassic sandstones, etc.; but I. C. White's account of the bowlder conglomerates associated with a low grade of coal and Permian plants in the state of Santa Catharina, e.g., at Orleans, shows that tillite continues to latitude 28°.[1] His map of the Tubarão series, which includes the Orleans glacial conglomerate, extends the tillite to the southern end of Brazil, in Rio Grande do Sul, though his account does not specially mention bowlder conglomerates as having been observed in that part of the country.

Guillemain, by finding tillite with striated stones at Fraile Muerto in northern Uruguay, not far from the boundary of Brazil, as noted in the introduction, continues the region of glaciation still farther to the south. Including the 500 kilometers reported from São Paulo this gives a length of about 1,500 kilometers from northeast to southwest, running in latitude from $22\frac{1}{2}°$ to about $32\frac{1}{2}°$. The tillite has not yet been found to outcrop continuously for this long distance, but the known localities are sufficiently numerous to make its continuity highly probable. Its known width is estimated at from 50 to 100 kilometers in São Paulo, but it is unknown how far it extends beneath the Triassic sediments and trap-sheets to the northwest.

TILLITE IN SIERRA DE LA VENTANA

There is a long gap between the Permo-Carboniferous deposits of Brazil and northern Uruguay and the nearest outcrops of tillite discovered in Argentina, which are in the Sierra de la Ventana not far from Bahia Blanca. Dr. J. Keidel, chief of the Geological Section of the Argentine Survey, was good enough to plan an excursion to this locality for me. A rail journey of 537 kilometers

[1] I. C. White, *Relatorio Final on the Brazilian Coal Fields*, 1908, pp. 11–13 and 51.

southwest from Buenos Aires brings one to the small station among the hills, after passing a vast stretch of prairie-like pampas with few or no outcrops of rock. The Sierra rises as rocky ridges with deep valleys between, one of them followed by the river Sauce Grande and others by its tributaries.

The railway crosses the river just south of the station and follows up the valley of a small stream in the Arroyo Negro. The best exposures of tillite are found in the railway cuttings along the Arroyo within seven kilometers of Sierra de la Ventana, and these will be described first.

The unweathered tillite is dark, bluish gray and entirely different in appearance from the usually red or brown and much-decayed tillite of Brazil. The rock is hard and shows some slaty cleavage, and the stones scattered through it are often a little squeezed or broken and slightly step-faulted. The weathered tillite is greenish or yellowish and crumbles somewhat readily, setting free the inclosed stones, but from the unweathered rock it is difficult to extract them unbroken. The fresh tillite is very like that from some outcrops of the Dwyka in South Africa, where the rock has undergone squeezing and distortion in mountain-building operations; and it closely resembles the Huronian tillite of Cobalt and might easily be taken for it in hand specimens.

The pebbles and bowlders inclosed include several species of rocks, granites and hard sandstones being commonest. They are seldom more than half a meter in diameter and have the characteristic shapes of glaciated stones. A considerable number have well-striated surfaces and are typical products of ice action.

In some of the cuttings cross-bedded quartzite and more or less water-formed conglomerate occur also, apparently interbedded with the tillite; and in several places quartzite overlies the tillite conformably. The base of the tillite was not seen in the railway cuttings, and a search was made for it to the north, where a small stream flows toward the Sauce Grande, but in vain. On this stream the tillite has been squeezed into schist conglomerate with a marked cleavage, reminding one of the Temiscaming and Doré conglomerates of Ontario. A search still farther north showed no solid rock for several kilometers until the base of the northern range

of hills was reached, where quartzite, mica schist, and slate were encountered.

Sections were examined a few kilometers up the river from the station and several fresh-looking outcrops of tillite were found at the water's edge. Ascending the slopes from such outcrops one finds weathered tillite for a few hundred yards, then a cliff of tillite, followed by a covered belt where only quartzite pebbles can be seen for a height of about 15 or 20 meters. A second cliff of tillite reaches 85 meters above the river and is followed by quartzite to the top of the ridge. The lower bed of quartzite seems to be interglacial, corresponding to the band of quartzite and water-formed conglomerate seen in the railway cuttings.

A section a kilometer or two down the Sauce Grande shows no base to the tillite, which has a thickness of 90 meters, as determined by aneroid, and is covered by quartzite including a band of tillite. None of the sections was entirely satisfactory, since on the gentler slopes the solid rock is more or less hidden; but the thickness of the glacial beds seems to be not less than 60 meters and may be much more than that.

An excellent account of the glacial deposits of Sierra de la Ventana is given by Keidel in *La Geologia de las Sierras de la Provincia de Buenos Ayres* (1916), as mentioned in the introduction to this paper; and the statement is made that the origin of a number of the inclosed bowlders is unknown. Keidel puts stress on the resemblance of these deposits to the Dwyka, but gives no proofs of their age except that they are later than the Devonian, as shown by the inclusion of pebbles of limestone with Devonian fossils. The hard and somewhat metamorphosed character of the rock, which seems to suggest a greater age, is to be accounted for by the action of orogenic forces. One of Keidel's plates represents the tillite as somewhat folded in a way that would add to the apparent thickness of the bed, but in my own field work no clear evidence of folding was seen, though compressive action was evident.

TILLITE NEAR SAN JUAN IN WESTERN ARGENTINA

Following a plan suggested by Dr. Keidel an excursion was made to exposures of tillite in western Argentina somewhat south of

San Juan. The nearest point to the outcrops on the railway between San Juan and Mendoza is at Paradero, kilometer 489. The railway traverses a desert country covered with sand and stones with isolated hills of rock not far to the east and the loftier Chico de Zonda, a range of foothills of the Andes, about eight kilometers to the west, as shown on Stappenbeck's geological map of the region. Walking westward over the desert from the railway there is a gentle rise for two or three kilometers, followed by low ridges between profound ravines, apparently cut by temporary streams due to cloud-bursts in the mountains. At about five kilometers west there are steeply tilted red shales dipping westward, followed by hills of a green, basic eruptive, greatly weathered, and then high cliffs of gray limestone. In the latter rock, fragments of crinoids and a syphon of orthoceras were found. It is indicated on the map as Silurian.

A little to the south of this section, where a narrow valley penetrates rugged hills, a greenish-gray shaly or slaty rock occurs, crumbling to fine débris on the surface, and including one or two bands of dark-brown pebbles and larger stones (Fig. 2). Most of the stones are fairly well rounded, as if rolled on a beach or in a river, and many have been broken and recemented. Frequently they have been broken again where they lie on the surface, probably by alternations of heat and cold.

A number of these stones are striated, often on more than one face. The largest seen was half a meter or somewhat less in diameter and was strongly scored. The stones are mainly basic eruptives, quartzite or limestone, the last too much attacked to show marks of glaciation. These stones appear to have been imbedded in the weathered, shaly rock, and in a ravine near by a few isolated ones are found still inclosed. The series appears to be tilted, but the dip and the limits of the bowlder bed could not be sharply determined, and in places two bowlder beds occur separated by a few meters of shale. These outcrops of loose, striated stones were followed for nearly a kilometer in a southerly direction, running parallel to the strike of the rocks in the foothills.

Somewhat to the southwest, where the narrow valley is steep-walled and approaches the cliffs, a side ravine disclosed an abso-

lutely different section, in which a bowlder conglomerate rudely stratified in parts rises as a ridge about 30 meters high. This is of a kamelike character and includes sand, gravel, and stones of all sizes up to a meter in diameter. They are often rounded, but may be of various shapes and consist of many kinds of rocks—granite,

FIG. 2.—From tillite south of San Juan, Argentina

gneiss, quartzite, vein quartz, sandstone, and limestone having been observed. Striated stones seem rare, only one poorly marked one having been found. It may be remarked, however, that in Pleistocene kames also it is unusual to find distinctly striated stones. Beneath the kamelike bed there are two or three meters of sandstone, and across a wide valley to the south a cliff shows six or seven meters of the conglomerate underlying, apparently

conformably, a hundred meters or more of sandstone with a westward dip.

The two types of deposit just described are as different as possible, though both seem to be glacial, but I was unable to determine how they are related to one another, since there has been folding, faulting, and squeezing during the formation of the mountain range, rendering the relationships complicated.

Before leaving Buenos Aires, Dr. Keidel had referred to two tillites, a lower and an upper, corresponding probably to the two deposits just described. He mentioned also that near the lower tillite Talchir plants had been found, and some distance farther south Kharbari plants, giving a clue to the age of the deposits. He has also found tillite to the north of San Juan, reaching in one place latitude 28°, and has discovered a striated surface of Devonian limestone beneath the tillite. Specimens of the tillite and of the glaciated surface are to be seen in the Museum of the Survey on Calle Maypu in Buenos Aires. His account of the very interesting glacial deposits in the western foothills of the Andes must be awaited for details as to their general features and relationships, but I am able to confirm his statements as to the glacial character of the beds so far as seen by myself.

CONCLUSIONS

From the descriptions given it will be seen that there are three widely separated regions of known Permo-Carboniferous glaciation in South America, the deposits differing much in appearance and lithological character, but all showing plainly the effects of ice action. The Brazilian tillites are the most widely distributed and the least changed. They occur along the dissected edge of a tableland rising several hundred meters above sea-level and dip gently inland beneath sandstones and trap-sheets of the early Mesozoic. One or two diamond-drill cores prove that the tillite extends for 50 kilometers or more beneath the Triassic beds, but how much farther they go in that direction is unknown. There can be no doubt that they once reached farther seaward, so that the original ice-covered area must have been much greater than the present known area of tillite. As marine fossils have been found by Oliviera interbedded with the tillite on the Rio Negro in the state

of Parana,[1] we may conclude that the region was at that time not a tableland but a comparatively low plain. In any case the whole character of the widespread, almost flat sheet of tillite in southern Brazil is such as must have resulted from ice action of the continental type. Mountain glaciers could not have provided so extensive, uniform, and relatively horizontal a deposit as the Brazilian geologists have found.

From what center the ice spread out is not known, though the numerous bowlders of granite and gneiss suggest a motion inland from the belt of Archean along the Atlantic coast. In that case the ice-sheet must have extended far toward the southeast, perhaps beyond the present edge of the continent. However, there are granites and gneisses farther west, and outcrops of these rocks which existed in Carboniferous times may lie buried under later deposits toward the west or north. The bowlders of ancient conglomerate containing jasper may some day be traced to their source, giving evidence of the direction in which the ice moved.

As to the tillites of the Rio Sauce Grande and of the belt along the foothills of the Andes near San Juan, the areas known to be covered by them are so small that local mountain glaciation might perhaps account for them; though the fact that tillite of the same age occurs on the Falkland Islands and that a great ice-sheet covering many thousands of square miles reached sea-level a few hundred miles to the north or east suggests that a very large part of South America must have been ice covered. It is not unlikely that the areas of ice action coalesced to form a single great sheet 1,300 miles or more in diameter and covering hundreds of thousands of square miles, something comparable to the vast continental ice-sheets of Europe or North America in the Pleistocene. The northern edge of this ice-sheet reached at least one degree into the tropics in Brazil; and this occurred, not on high mountains, but on comparatively low ground, as shown on a former page.

Recent advances in the study of the South American Permo-Carboniferous glacial deposits bring that continent into the same rank as South Africa and Australia with respect to the area then covered by ice, while India has been much surpassed. The magnitude of the geological problem involved is growing from year to

[1] Woodworth's *Report*, p. 29.

year, and the difficulty of accounting for such tremendous climatic changes is by no means lessening. The fact that the most extensive ice-sheets were in the Southern Hemisphere and that India only in the Northern Hemisphere shows important glaciation at the end of the Carboniferous forms one of the puzzling features of the problem. The idea that a change in the position of the poles could account for Permo-Carboniferous ice-sheets has been completely set aside by the discoveries in South America, since with the South Pole planted in the middle of the Indian Ocean southern Brazil would have been within the tropics.

The theory of glaciation due to elevation is disproved also by the evidence from Australia and South America, showing that the ice-sheets reached sea-level; and in any case it is inconceivable that such vast areas could all be elevated the necessary thousands of feet at the same time. Even if they were sufficiently elevated to give the required temperature, a large enough supply of moisture could hardly be arranged for on the greatly enlarged continents which this implies. The high tableland of the Andes is arid or semi-arid at present, and even the loftier peaks usually show little snow and few and small glaciers. It is evident that elevation alone will not account for the millions of square miles of *nevé* and ice-fields which must have covered much of India, Africa, Australia, and South America.

The most satisfactory theory is that of refrigeration due to changes in the earth's atmosphere; but even this fails to explain why Europe, Northern Asia, and North America should have been so little affected when great regions in other parts of the world were powerfully glaciated. One would expect that the change of climate affecting the tropics in India, Australia, and South America, and probably also in Africa would have been felt everywhere. It may be, however, that while the refrigeration was universal the supply of moisture necessary to form glaciers was lacking in Northern Asia, Europe, and North America. They may have had no ice-sheets for the same reason that Siberia was left uncovered with ice in the Pleistocene Ice Age; because the position of the open seas and the direction of the atmospheric circulation made them relatively dry regions with little snowfall.

THE SUBPROVINCIAL LIMITATIONS OF PRE-CAMBRIAN NOMENCLATURE IN THE ST. LAWRENCE BASIN

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INTRODUCTION

The detailed geological work carried on in recent years throughout the southern part of the Canadian pre-Cambrian shield has shown that the geological succession in the ancient terranes of this territory is regionally less uniform and includes a greater number of rock series than was formerly supposed. Moreover, it has become evident that the widespread correlations implied by the use of the same nomenclature nearly everywhere throughout this great pre-Cambrian province assumes much more with regard to the regional succession in these ancient rocks than is actually known.

Although it is not possible generally to demonstrate with mathematical conclusiveness that geological formations occurring in different localities are equivalent, nevertheless the premature use of the same name for formations, the correlation of which is open to question, or the continued use of the same name for formations after it has become evident that their correlation is in doubt, is misleading, and is an obstacle rather than an aid in geological investigation. Hypothetical correlations of groups of rocks occurring in widely separated districts may serve for comparison or as a stimulus to investigation, but all the advantages of such tentative correlations may be attained by using a general terminology (Proterozoic, Archaeozoic, etc.) and thereby avoiding the definite correlations implied in the use of names of local origin. In the pre-Cambrian province which occupies the northern part of the St. Lawrence River basin there are four geographically and geologically separate subprovinces: (1) the region northwest of

[1] Published with the permission of the Director of the Geological Survey of Canada.

Lake Superior, (2) the region south of Lake Superior, (3) the region extending northeastward from Lake Superior and Lake Huron to Lake Timiskaming and Lake Mistassini, and (4) eastern Ontario and the lower St. Lawrence, with which might be included the Adirondack region. With the possible exception of some of the late pre-Cambrian series occuring in the Lake Superior and the Timiskaming subprovinces, the evidence upon which the rocks of these separate regions can be correlated is exceedingly meager, and for the present, at least, the only logical course would seem to be to build up a separate nomenclature in these various subprovinces by using those names already defined in these localities, supplemented by such local new names as become necessary from time to time as geological investigation is continued.

OBJECTIONS TO AN INTER-SUBPROVINCIAL NOMENCLATURE

The widespread correlations implied in the use of a common nomenclature throughout all the pre-Cambrian subprovinces of the St. Lawrence basin has been based on the assumption that the succession of formations within the various subprovinces has been worked out to practical completeness, and on the application of certain principles by which the correlation of the various formations in these widely separated areas is presumed to be established. The purpose of the following discussion is to point out that the assumption that our knowledge of the succession of formations in any of the subprovinces is complete is open to question and that the principles by which pre-Cambrian rocks are generally correlated are in part inapplicable and as a whole quite inadequate for the establishment of a pre-Cambrian nomenclature embracing all the territory in the St. Lawrence basin in which pre-Cambrian rocks occur.

OUR KNOWLEDGE OF THE SUCCESSION OF FORMATIONS IN THE SUBPROVINCES INCOMPLETE

The numerous regional classifications of the pre-Cambrian rocks of the St. Lawrence basin which have appeared from time to time in recent years, and the use of such terms as Keewatin, Laurentian, and Huronian nearly everywhere throughout this great pre-

Cambrian province and at points hundreds of miles from those in which these names were originally defined, would seem to imply that our knowledge of the succession of formations within this vast territory was much more complete than is actually the case. Only a very small part of the territory in the St. Lawrence basin in which pre-Cambrian rocks occur has been actually mapped in detail, and even in those localities which have been mapped in considerable detail and have been regarded in the past as type areas the succession of formations formerly supposed to be present has in many cases been considerably modified by more recent investigation.[1]

THE PRINCIPLES OF PRE-CAMBRIAN CORRELATION INAPPLICABLE OR INADEQUATE

Continuity or approximate continuity of outcrop.—The principle of continuity, or approximate continuity, of outcrop is the most conclusive of all the means by which the relationship of rocks can be determined. But it is inapplicable to the correlation of the various rock series occurring in the different pre-Cambrian subprovinces for the reason that these are geographically and in part geologically separate from one another. Between the Timiskaming and the Grenville subprovinces there intervenes an extended belt of banded gneisses; between the Timiskaming and the western subprovinces there are the little-known wooded pre-Cambrian highlands on the north and overlapping Paleozoic sediments on the south; and between the northwestern and the southwestern subprovinces lie the waters of Lake Superior. If, therefore, a common nomenclature be employed for all the pre-Cambrian subprovinces of the St. Lawrence basin, this nomenclature must be based on other less conclusive principles of correlation.

Lithological similarity.—This criterion has been widely applied in the correlation of pre-Cambrian formations, although it is in reality of very limited application; for the pre-Cambrian rocks of

[1] A. C. Lawson, *Geol. Surv. Can., Mem. 28*, 1912, and *Mem. 40*, 1913, p. 4.
W. G. Miller and C. W. Knight, *Ann. Rep. Ont. Bureau of Mines*, XXII, Part 2, 1914.
R. C. Allen and L. P. Barrett, *Jour. Geol.*, XXIII (1915), 689.
W. H. Collins, *Geol. Surv. Can., Sum. Rept.*, 1916, p. 183.
C. R. Leith and R. C. Allen, *Jour. Geol.*, XXIII, 703.

the Canadian shield, both sedimentary and igneous, are for the most part common types which might be deposited or intruded or extruded in any epoch of earth history. It has been largely on the basis of this principle that the name Keewatin, first applied by Lawson to the metamorphosed basal volcanic complex occurring in the region northwest of Lake Superior, was extended, first to the Timiskaming region and later to eastern Ontario, a district nearly 1,000 miles distant from the locality in which the term was originally defined; yet volcanic rocks of this character are among the most common in the earth's crust. They are represented at some point in nearly all the pre-Cambrian series of the St. Lawrence basin; are likewise abundant in later formations throughout the world, as in Great Britain, where they occur at numerous horizons ranging in age from the early Palaeozoic to the Tertiary; and are in process of formation at one or more points on the earth's surface today. As a consequence of this unscientific method of correlation the name Keewatin, although presumed to represent a definite formation, in reality is now applied in the Canadian pre-Cambrian subprovinces to any highly metamorphosed volcanic rock without regard to age.

Similar stratigraphical succession of beds.—The larger part of the pre-Cambrian surface rocks of the region under consideration are volcanic flows or clastic sediments, in which a regular sequence of strata is uncommon, and this criterion is therefore inapplicable except to the late pre-Cambrian rocks. It has been especially useful in the mapping of the Huronian series in the Timiskaming subprovince, the Lower Marquette in the region south of Lake Superior, and the Animikie sediments in the region northwest of Lake Superior.

Similar serial succession.—The widespread correlation implied in the nomenclature applied to the pre-Cambrian rocks of the St. Lawrence basin has been based to a considerable extent on this principle, although the apparent similarity in the serial succession may very frequently be explained in other ways. The principal objection to the use of this criterion is that it neglects to consider the possibility of overlap. Sedimentary rock series are not generally deposited continuously or uniformly over immense areas, and

where they have been deposited they are very commonly swept away in part by later erosion, before succeeding series are laid down. Moreover, the pre-Cambrian surface rocks are to a large extent volcanic flows or land sediments, and on this account are much more discontinuous than sediments of marine origin.

Mode of origin of formations.—This criterion is of limited application; for sediments originating in the same way may be deposited during different geological epochs, and likewise sediments originating in different ways may be deposited contemporaneously in adjoining localities. It might be of value in the correlation of certain uncommon types, such as glacial deposits, which generally occur only at long intervals in geological time.

Relationship to batholithic intrusions.—The relationship of the pre-Cambrian surface rocks to the great epochs of batholithic invasion is of great assistance in correlation and may possibly eventually prove to be the most important of all the criteria used in the classification of the pre-Cambrian rock series into major groups; for geological investigation throughout the world has shown that batholithic intrusions are an accompaniment of mountain-building movements in the earth's crust, and are thus directly related to the great regional changes in rock structure, to regional metamorphism, and to the uplifts which give rise to the great erosion intervals which form the dividing lines between the great pre-Cambrian terranes. Some of the applications and limitations of batholithic invasion in rock correlation are included in the following:

Batholithic massifs are co-extensive with the mountains they underlie, and since mountains are generally extensive and linear the massif should also be extensive and linear. The extent of the outcrop of the massif will depend, of course, on the extent to which unroofing has been carried. In the Rocky Mountains, for example, unroofing has apparently only begun; in the Coast Range batholith of the Pacific Coast, on the other hand, unroofing is almost complete; and in some of the pre-Cambrian batholiths of the Canadian shield not only is the unroofing largely completed, but the batholith has also been reduced to base level.

If two batholithic massifs have been intruded in a given region the younger may displace the first. Hence the conspicuous

structural features of the region would be those of the younger massif, and all evidence of the former presence of the older batholith might be destroyed except for such remnants as happened to remain in association with the roof rocks in the geosynclinal belts.

Mountain-building periods and hence also periods of batholithic intrusion occur at long intervals separated by erosion periods and the development of peneplains.

The rocks in the vicinity of an intrusive batholithic mass are generally highly folded and metamorphosed; hence, if in a given area in the vicinity of a batholith flat-lying rocks occur which have not been greatly metamorphosed, it may be inferred that they have not been intruded by the batholith.

Batholiths are composite, and their intrusions continue during long intervals of time so that their various parts are only approximately of the same age.

Batholithic rocks are lithologically so similar that it is generally impossible to distinguish between batholiths of different ages except by means of their relationships to other rocks of which the age is known.

Recently A. C. Lawson has contributed an interesting paper to the discussion on the "Correlation of the pre-Cambrian Rocks of the Region of the Great Lakes," in which he formulates the hypothesis that throughout the region extending from the Adirondacks to northwestern Ontario there were in pre-Cambrian time "two and only two periods in which great granitic batholiths were developed in the earth's crust." On the basis of this hypothesis he correlates all the pre-Cambrian rocks occurring in the territory to which his hypothesis is applied.[1] This hypothesis, if true, would undoubtedly greatly simplify the problems of pre-Cambrian nomenclature and correlation in the region under discussion; but an examination of the hypothesis from either a deductive or an inductive standpoint seems to indicate that it is an unwarranted assumption.

The principal fact on which Lawson's hypothesis of two and only two periods of granitic batholithic intrusion was based was that at the time the hypothesis was formulated only two periods

[1] *University of California Publications*, X (1916), 1–19.

of batholithic intrusion had been recognized in most of the pre-Cambrian subprovinces of the St. Lawrence basin. There is a very apparent reason, however, why two and only two batholithic intrusions can be recognized in a single locality, namely, that if a third batholith were intruded in a district where two batholiths were already present the evidence of the former presence of one or other of the older batholiths would probably disappear.[1]

If it be assumed that batholithic intrusions represent the interior portions of mountain chains it is obvious that the prolonged erosion, which generally follows an orogenic uplift, must inevitably result in the stripping off of the roof rocks from the underlying massif and the replacement of surface rocks by plutonic types in the district where the uplift has occurred; also that successive crustal movements of the orogenic type in the same or adjoining localities must eventually bring about the disappearance of all trace of rocks originally present in such zones of disturbance. It is probable that within the base-leveled pre-Cambrian complex which underlies the larger part of the Canadian shield evidence of the presence of more than two separate periods of batholithic intrusion would not generally survive in a single locality. If, however, the succession of formations can be determined over an extended area, as where less metamorphosed late pre-Cambrian sediments occur, the number of batholithic intrusions which can be recognized might be increased. Thus, as a result of the more extended areal geological studies of recent years, evidence is accumulating that at least three definite periods of batholithic invasion are represented in several of the pre-Cambrian subprovinces of the St. Lawrence basin.

The folded and metamorphosed pre-Cambrian rocks occurring along the southern margin of the Canadian shield have in the main a northeasterly structural trend; likewise the granitic batholiths, so far as their areal distribution has been determined, are distributed in northeasterly trending zones; thus the region (approximately 1,000 miles in length) extending from the Adirondacks to the Lake of the Woods, to which Lawson's hypothesis has been applied, lies almost transverse to the regional trend of pre-Cambrian folding,

[1] A. C. Lane, *Am. Jour. Sci.*, XLIII (1917), 42.

mountain building, and batholithic invasion. Moreover, mountain systems throughout the world are generally narrow and linear and, where zones of crustal disturbance composed of several mountain systems, such as the cordillera of North America, occur, the systems composing the zone are generally of varying age. Hence, if granitic massifs represent the interior of mountain systems exposed by denudation, it is more probable that the northeasterly trending pre-Cambrian batholithic zones of the St. Lawrence basin, instead of belonging to two and only two periods of batholithic intrusion, in reality represent several periods of batholithic development.

Relationship to igneous intrusions other than batholith.—Igneous intrusions other than batholiths, especially if they are composed of unique rock types, can likewise be employed for purposes of correlation, but generally only within a single subprovince. The principle has been used for inter-subprovincial correlation in the case of the late pre-Cambrian diabase intrusions, however, all of which have been generally regarded as Keweenawan in age.

Folding and metamorphism.—Since folding and metamorphism are accompaniments of mountain building and batholithic invasion, these criteria are in reality included under the head, "Relationship to Batholithic Intrusions." It can be generally inferred that in the same district those rocks which are most highly folded and metamorphosed are the oldest in age. This does not follow in the case of widely separated regions, however; for it has been found that rocks which are flat-lying and slightly metamorphosed in one district may be highly folded, metamorphosed, and intruded by granite batholiths in another locality.

CONCLUSION

From the preceding discussion the following conclusions may be inferred: that the regional succession of formations within the pre-Cambrian of the St. Lawrence basin has not yet been sufficiently worked out for the establishment of a definite nomenclature applicable to the whole of this territory; that, since the St. Lawrence basin extends for approximately 1,000 miles in a direction transverse to the trend of pre-Cambrian mountain building and batholithic intrusion, it is theoretically improbable that the

geological history of the various parts of this territory in pre-Cambrian time would be the same; that the geological succession of formations so far determined to be present in these various parts indicates that their history has not been the same; that the pre-Cambrian formations occurring in the St. Lawrence basin fall naturally into a number of separate subprovinces; and that it is advisable for the present that a separate nomenclature be employed in each of these subprovinces.

The principal advantages that might be attributed to the widespread correlations implied in the present nomenclature applied to the pre-Cambrian rocks of the St. Lawrence basin are that they serve as tentative hypotheses for the investigator in the field, and as summaries of existing knowledge for the science as a whole. But it is doubtful whether tentative hypotheses have a place in geological nomenclature, and furthermore, for the investigator familiar with the facts in the field, tentative correlation tables indicating the most probable relationships of the formations occurring in the various subprovinces can afford all the advantages of a regional nomenclature, and for those not familiar with the facts in the field a general classification from which names of local origin are excluded could be used. Such a classification might be less definite, but it would be scientific, since it would express what is actually known, or what is at least generally accepted, by those familiar with the facts in the field rather than tentative hypotheses.

CORRELATION OF THE EARLY SILURIAN ROCKS IN THE HUDSON BAY REGION[1]

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The oldest rocks of Silurian age known in the Hudson Bay region are present in the banks of Nelson River, about forty-five miles above tide-water. The best exposure is about four miles below the outcrop of Richmond strata at the lower Limestone Rapids of the river, where a vertical ledge outcrops to a height of 28 feet above low water. The rocks are nearly horizontal or gently undulating, and consist of yellowish-brown, rather fine-grained dolomite, in layers 4 to 10 inches thick. Masses of this dolomite form a pavement along the banks of the river at intervals for several miles below the main exposure, indicating that the river is actively cutting into these strata in places east of their actual outcrop.

The fossils in this dolomite appear to be restricted to a narrow zone in the lower part of the bed. The most abundant are molds and casts, mostly of the ventral valve, of shells of the species described by Whiteaves as *Conchidium decussatum* from the basal Silurian strata at the Grand Rapids of Saskatchewan River. These shells are in places so crowded together as to make up the greater part of the rock layers, just as they occur at the Grand Rapids outcrop, where they are also restricted to a narrow zone.

The shells of this species found in the Nelson River region show a wide variation in the ratio of their length and width, in the degree of convexity or galeation of the ventral valve, and in the development of the mesial fold on the ventral valve. Some of the partially exfoliated shells even show a distinct mesial sinus extending from the beak over the umbonal region of the ventral valve, which becomes obsolete or is transformed into a mesial fold in the middle

[1] The strata discussed in this paper probably fall within the later half of the Oswegan series of the New York Classification.

and anterior portions of the valve. Similar variations occur in the shells of this species found at the Grand Rapids of the Saskatchewan River, described by Kindle[1] as follows:

> *Conchidium decussatum* belongs to a group of shells in which the specific characters are very plastic. . . . . The ventral valve shows three well-marked types of contour, viz.: (1) Strongly convex with a more or less clearly defined median ridge extending from the umbonal region to the front of the shell. (2) Very convex with tumid umbonal region rounding regularly from the median region to the lateral and anterior margins without trace of median ridge. (3) Strongly convex in median and anterior region with or without median ridge, but with a broad shallow sinus extending from the beak across the umbonal region. These three types of contour make striking contrasts when individuals in which they are best developed are compared; but the intermediate forms, in which neither the presence of ridge or sinus nor their entire absence can be positively stated, make difficult any attempt to discriminate them as distinct varieties.

It is noteworthy that the shells showing a mesial sinus in the umbonal region of the ventral valve are young forms, and the writer is convinced that the more striking differences shown in the ventral valve of this species represent different growth stages in the individuals; the youthful stages show a mesial sinus from the beak across the umbonal region or farther anteriorly, while in the old stages the mesial sinus has disappeared and a distinct mesial fold is frequently developed.

The above-mentioned characters are the principal ones on which Twenhofel founded the genus *Virgiana*, and it seems certain that the species formerly known as *Conchidium decussatum* really belongs to the genus *Virgiana*. Through the kindness of Dr. Kindle a comparison was made of the shells of this species from Nelson River with those from the Saskatchewan region in order to make sure of the identity of the species from the two localities. The shells from the Grand Rapids locality also show unmistakably the characters of the genus *Virgiana*[2] to which this species is here referred.

[1] E. M. Kindle, "Notes on the Geology and Paleontology of the Lower Saskatchewan River Valley," *Geol. Surv. of Canada, Mus. Bull. No. 21* (Geol. Series No. 30), October 14, 1915, p. 16.

[2] Specimens of these shells were also sent to Dr. Twenhofel, the author of the genus, who agreed with the writer that they were true *Virgianas*.

The variation presented in the ventral valve of this species is similar to that shown in the shells described by the writer as *Virgiana barrandei* var. *mayvillensis*, and *V. barrandei* var. *major* from the Mayville limestone in Wisconsin. At the time those varieties were described the only other known representatives of this genus were *Virgiana barrandei* and a variety of that species occurring in the Becsie River (earliest Silurian) formation of Anticosti Island, from which it was thought that they might have been derived. However, the *Virgiana* shells from Wisconsin are now known to be more closely related to *Virgiana decussata* than to the Anticosti forms. In recognition of this relationship it is here proposed to elevate the varieties *Virgiana barrandei* var. *mayvillensis* and *Virgiana barrandei* var. *major* to the rank of species. The former differs from *Virgiana decussata* in having somewhat fewer and coarser radiating plications, less numerous concentric markings, and usually is relatively wider in the anterior part of the shell. *Virgiana major* is a larger shell than *V. decussata*, and generally has a much more strongly developed keel-like median ridge on the ventral valve.

Regarding the age of the strata containing these shells in the Grand Rapids region Kindle[1] says:

> Close comparison between the faunas of the Grand Rapids section and those of eastern Silurian sections, owing to the dearth of common species, is difficult. The dominance in the lowest (Silurian) fauna of this section of such a genus as *Conchidium*, however, makes it probable that the base of the section represents a Silurian horizon not earlier than the Clinton, and probably of early Niagaran age.

This argument is no longer applicable, since instead of belonging to the middle Silurian genus *Conchidium*, the species in question belongs to the genus *Virgiana*, which is an early Silurian genus known elsewhere only from strata of pre-Niagaran (Alexandrian) age.

The early Silurian age of the strata containing *Virgiana decussata* in the Grand Rapids of the Saskatchewan and the Hudson Bay regions can be shown by their relations to associated strata in different areas. In the Grand Rapids region the layers containing *Virgiana decussata* are succeeded by strata which contain the fossils

[1] E. M. Kindle, *op. cit.*, p. 9.

Pterinea occidentalis, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina*. In the Hudson Bay region a zone a few feet above the horizon of *Virgiana decussata* furnished shells of *Camarotoechia? winiskensis*, *Pterinea occidentalis*, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina*. In the northern peninsula of Michigan[1] early Silurian strata containing *Camarotoechia? winiskensis*, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina* overlie the strata containing *Virgiana mayvillensis*, which is a near relative of *Virgiana decussata*. In eastern Wisconsin *Virgiana mayvillensis* occurs in the uppermost layers of the Mayville limestone above which there is a stratigraphic break, the horizon of *Camarotoechia? winiskensis*, *Isochilina grandis* var. *latimarginata* and *Leperditia hisingeri* var. *fabulina*, present farther east in northern Michigan, having been removed by erosion. However, there is no doubt that the strata which in northern Michigan contain *Virgiana mayvillensis* correspond in age to those containing the same species in the upper part of Mayville limestone in Wisconsin, as they are clearly a northeastward continuation of the same beds. The relations of the strata containing *Virgiana* to the overlying and underlying beds in the regions above described are shown in the columnar sections in Fig. 1.

In Wisconsin there was found in the quarry near Peebles a zone only a few feet below the horizon of *Virgiana mayvillensis* and apparently conformable with it, which yielded such characteristic Edgewood species of fossils as *Dalmanella edgewoodensis*, *Rhynchonella? janea*, *Rhynchotreta parva*, and *Atrypa putilla*. The position of *Virgiana mayvillensis* in Wisconsin in the upper part of the Mayville limestone, which at a slightly lower level contains a characteristic Edgewood fauna, indicates that this horizon is Alexandrian (late Edgewood) in age. It is also significant that the strata containing *Virgiana mayvillensis* in Wisconsin seems to occupy about the same position in the Silurian column as do the strata which contain *Virgiana barrandei* in the Becsie River formation of Anticosti Island.

[1] T. E. Savage and H. F. Crooks, "Early Silurian Rocks of the Northern Peninsula of Michigan," *Am. Jour. of Science*, XLIV (January, 1918), 59–64. In the lists of fossils given in this paper the name of the species given as *Atrypa putilla* should have been written aff. *Atrypa putilla*.

CHART SHOWING RELATIONS OF EARLY SILURIAN STRATA CONTAINING VIRGINIA IN DIFFERENT REGIONS

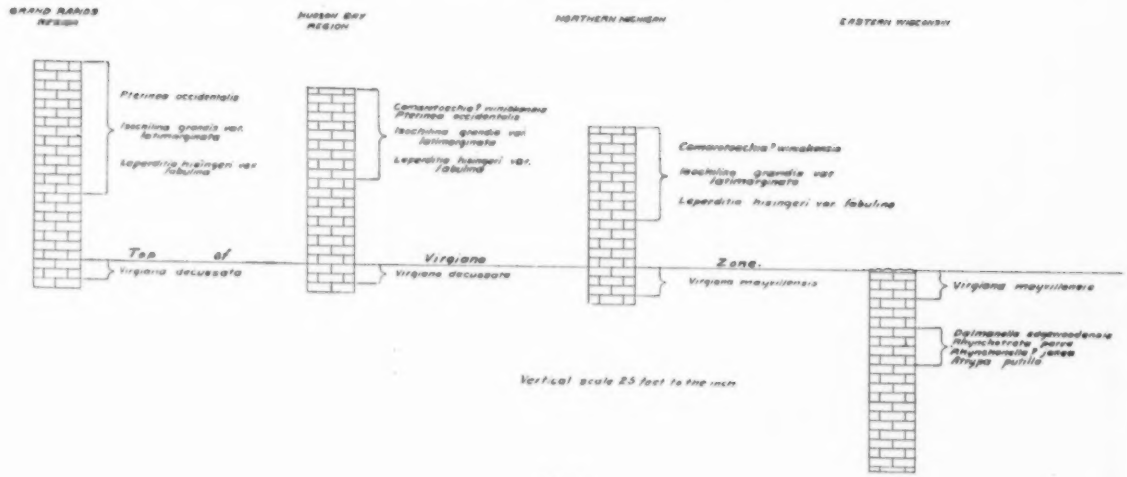

FIG. 1

In Michigan the strata containing *Camarotoechia? winiskensis*, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina* conformably overlie the *Virgiana mayvillensis* beds, and thus are thought to correspond in age to about that of the Sexton Creek or Kankakee limestone which overlies the Edgewood in Illinois and Missouri, but they were deposited in a different geologic province.

The close correspondence in the fauna of the strata overlying the *Virgiana mayvillensis* zone in northern Michigan with that of the strata above the horizon of *Virgiana decussata* in the Hudson Bay and Saskatchewan regions leaves no doubt of the equivalence of the strata containing this fauna in the areas above mentioned. They also prove that the *Virgiana mayvillensis* zone in Wisconsin and Michigan, and the *Virgiana decussata* zone in the Hudson Bay and Saskatchewan localities represent the same stratigraphic horizon.

Besides the above-mentioned localities Hume[1] has found early Silurian strata containing *Camarotoechia? winiskensis*, and numerous ostracods in the Lake Timiskaming area that he correlates with the Cataract formation, which doubtless corresponds with the *Camarotoechia? winiskensis*, *Isochilina*, and *Leperditia* horizon in the regions above described. The age assigned to this horizon by Hume agrees with that given by the writer above.

Kindle[2] found Silurian strata several hundred miles north of the Grand Rapids locality, in the vicinity of the Pas, from which he obtained the fossils *Camarotoechia? winiskensis*, *Pterinea* cf. *occidentalis*, and *Leperditia* cf. *hisingeri*. This fauna also indicates a horizon about equivalent to that of the Silurian in the Lake Timiskaming region and to the strata containing *Pterinea occidentalis*, *Isochilina*, and *Leperditia*, above the *Virgiana decussata* horizon in the Grand Rapids section, the latter horizon not being exposed in the more northern locality. From the similarity in the faunas of the *Virgiana* zone, and of the higher strata containing

[1] G. S. Hume, "Paleozoic Rocks of Lake Timiskaming Area, *Geol. Surv. of Canada*, *Sum. Rept.* (1916), pp. 188–92. Fossils reported by Charles Schuchert in a personal letter.

[2] E. M. Kindle, *op. cit.*, p. 12.

Camarotoechia? winiskensis, *Isochilina grandis* var. *latimarginata*, and *Leperditia hisingeri* var. *fabulina* in the regions above described it is inferred that during the time these strata were laid down the above-mentioned regions were a part of the same province or basin of deposition, which was rather broadly connected northward with the Arctic Ocean.

This extensive northern invasion, together with the nearly synchronous deposits of the Cataract formation in a basin connected eastward with the Gulf of St. Lawrence region, and of the Brassfield and Sexton Creek limestones which were deposited in a southern basin, indicates a much more extensive submergence of the continent during early Silurian (late Alexandrian) time than was formerly supposed.

The very close correspondence of the middle and late Ordovician and early Silurian rocks and faunas in the Saskatchewan and Hudson Bay regions is strong evidence that they were deposited in a sea that was continuous between these areas. The presence of middle Ordovician and early Silurian rocks and faunas in the Lake Timiskaming region[1] similar to those in the Hudson Bay region, and of late Middle and Upper Devonian strata in the vicinity of James Bay which probably originally extended south to the Timiskaming region,[2] indicates that this part of the ancient Laurentian or Canadian shield did not exist continuously as a land surface throughout the Paleozoic era, as has generally been assumed, but that during middle and late Ordovician time, in early Silurian, and probably also during late Middle and Upper Devonian time the northern seas, temporarily at least, covered the greater part of this shield on the south and probably also on the west of Hudson and James bays. Kindle and Burling[3] have previously shown that the seas probably also extended widely over the Laurentian upland southeast and east of Hudson Bay during the Paleozoic era.

[1] M. Y. Williams, "The Ordovician Rocks of Lake Timiskaming," *Geol. Surv. of Canada, Mus. Bull. No. 17* (Geol. Series No. 27), June 7, 1915.

[2] G. S. Hume, "Paleozoic Rocks of Lake Timiskaming Area," *Geol. Surv. of Canada, Sum. Rept.* (1916), p. 190.

[3] E. M. Kindle and L. D. Burling, "Structural Relations of the Pre-Cambrian and Paleozoic Rocks North of the Ottawa and St. Lawrence Valleys," *Geol. Surv. of Canada, Mus. Bull. No. 18* (Geol. Series, No. 28), July 23, 1915.

NOTES ON SEDIMENTATION IN THE MACKENZIE RIVER BASIN[1]

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INTRODUCTION

In the course of field work in the Mackenzie River region during the summer of 1917 the writer had an opportunity to observe various features in connection with the constructive and destructive work of the rivers and lakes traversed. The following notes relate to the lower Peace, the Slave, Athabasca, and upper Mackenzie rivers, and Great Slave and Athabasca lakes (Fig. 1). The making of these observations was incidental to other work, and they are assembled here as a fragmentary contribution to a knowledge of present-day work in continental sedimentation in the Northwest.

The parallel streams of clear and muddy water in the channel of the Mackenzie, its sloping bowlder-paved banks in marked contrast with the cut banks of the Peace and Slave rivers, and its relatively straight course are among the noteworthy features of this great river. The marked inequality in the rate of sedimentation on opposite sides of Great Slave Lake is one of the significant features in connection with the lacustrine sedimentation of the region. These and other factors relating to sedimentation in the Mackenzie basin will be discussed in the following notes.

MATERIALS OF THE VALLEY FLOORS

The valleys of the Peace and Athabasca rivers are throughout the major part of their courses cut deeply into the shales and sandstones of the Cretaceous formations. At Peace River crossing the Peace River flows in a steep-sided valley cut about nine hundred

[1] Published with the permission of the Director of the Geological Survey of Canada.

feet below the surface of the Cretaceous plateau. The Athabasca, where it joins the Clearwater, has cut its valley into the Cretaceous rocks to a depth of about five hundred feet. The lower portions of both streams, however, flow for considerable distances across a very broad, low, flat plain of recent origin, which is composed

FIG. 1.—Sketch map of the Mackenzie River basin

chiefly of fine silts and sands. These beds are of both lacustrine and fluvial origin and evidently of postglacial age. Near the river the fluvial beds are more in evidence than the lacustrine, but the latter probably have a far greater extent than the former. In the Peace River region the cut banks of sand rising in places 80 feet high or more above the water represent the bottom deposits of a

greater Lake Athabasca which was a contemporary of Lake Agassiz. Similar beds occur along the lower Slave River (Fig. 2), which belong to the period when a much greater Slave Lake was developing the

FIG. 2.—Lacustrine sediments on the Slave River near Salt River, representing deposits of a former greatly extended stage of Great Slave Lake. Photograph by E. J. Whittaker.

wave-cut cliffs and elevated beaches now found far back from its shores. The following section, taken above Little Rapids on the Peace, indicates the general character of these lacustrine beds:

1.	Forest bed and soil	1 foot
2.	Brown sand	3 feet
3.	Forest bed, etc	6 inches to 0
4.	Gray sand with pebble band in middle	1 foot
5.	Hard sand with limy bands	1 foot
6.	White marl	8 inches to 0
7.	Gray sand with calcined roots	2½ feet
8.	Marly sand	2 inches
9.	Gray even-bedded sand partly covered	30 feet

The broad low plain of lacustrine sands which have been extensively re-worked by the river, extends from the pre-Cambrian hills east of Slave River and the lower Athabasca many miles to the westward. It meets the foot of a plateau called the Caribou Mountains west of the Slave River, while a similar upland known

as the Birch Mountain projects shieldlike from the south into the low land between the Peace and the Athabasca rivers.

The banks of the Mackenzie for the first 200 miles below Great Slave Lake are in some places very low, particularly near the head of the river, though rising 50 to 150 feet above the stream in many places. But the materials in which the channel is cut are nearly everywhere either glacial drift or Devonian shales. It will be pointed out later that the till banks of the Mackenzie give rise to certain peculiarities of the river which are not found in the Slave, lower Peace, and Athabasca rivers, whose channels are cut largely in lacustrine beds.

RELATIVE TURBIDITY

The major part of the great volume of water comprising the upper Mackenzie River is gathered by two large rivers, the Peace and the Athabasca. The latter stream is filtered through Athabasca Lake before joining the Peace. The Peace, united with the Athabasca under the name of the Slave River, pours its flood of sediment-laden water into Great Slave Lake, which discharges it, freed of its burden of floating trees and suspended mud, into the head of the Mackenzie River. The filtered waters of the Slave and half a dozen other considerable streams which flow into Great Slave Lake unite in the upper Mackenzie to form a stream which, in both volume and clarity, is comparable with the upper St. Lawrence. This clear river issuing from the lower end of Great Slave Lake receives no stream of notable size for 150 miles, to the point where it is joined by the Liard from the west. The Liard drains a great area including all the easterly valleys of the Rocky Mountains between the head waters of the Peace and the Yukon. The large volume of the Liard is characterized by a high degree of turbidity. Its muddy waters join the clear waters of the Mackenzie at Fort Simpson, but for more than 160 miles below Simpson they fail to mix except in a limited zone near the middle of the river. During the canoe trip down the Mackenzie observations regarding the relative clarity of the water on the two sides of the river were made repeatedly. The following excerpts from my notes indicate the contrasts observed. Twenty-five miles below the mouth of the Liard River, a crossing from the east to the west bank was made to

observe the relative amounts of sediment on the two sides. On the east side the water was quite clear, the tip of an oar being visible as far down as its length. One third of a mile from the east bank the water showed a trace of sediment, the visibility in looking down into it along the side of an oar being noticeably less. The suspended matter gradually increased toward the west bank for a quarter of a mile. The last third of a mile on the west side held so much sediment that only indistinctly could the bottom of a cup 4 inches deep be seen through it. An oar could not be seen more than 3 or 4 inches below the surface of the water. "At old Fort Wrigley, 140 miles below the Liard, the water on the east side of the river is quite clear, no visible sediment is present, and visibility extends down 3 feet or more. On the west side the bottom of a cup 4 inches deep can be discerned through the water only very indistinctly. The contrast in driftwood also continues striking, being very abundant on the west and scarce on the east side." This contrast, though in a somewhat less marked degree, extended as far as New Fort Wrigley, 160 miles below the Liard, the northern limit of my journey. At Fort Norman a large river brings the clear waters of the Great Bear Lake drainage basin into the east side of the Mackenzie. This large accession of clear water to the east side doubtless results in keeping the eastern half of the Mackenzie comparatively clear to the head of the delta.

Thus we have the curious phenomenon of two rivers, one a clear and one a highly turbid stream, flowing side by side in the same channel without mixing except in a comparatively narrow zone. As a result the deposition of sediment differs markedly in amount and kind on the two sides of the Mackenzie. The islands of alluvial material which occur at various points in the river below the Liard are all confined to the western half of the stream. The abundant supply of drift logs which comes down the Liard furnishes a large amount of drift timber to the west bank of the Mackenzie. Comparatively little of it lands on the east bank.

DESTRUCTIVE AND CONSTRUCTIVE WORK OF THE RIVERS

The Slave River carries vast quantities of sediment into Great Slave Lake. It enters the lake through several narrow channels,

the mouths of the easternmost and westernmost of them being separated by more than ten miles. The lake water in front of the delta is, for some miles out, quite shallow. The submerged margin of the Slave River delta over several square miles is less than a half-foot in depth. This zone is strewn in most places by numberless logs and trees. Inside these comes a broad, irregular fringe of grass-covered land with no willows or other trees, too low for the bank to show. Farther up the delta some of the shores have been built up one foot or a little more above the late summer stage of the water and are covered with willows. Between these islands of the delta, with willow and other low trees, stretches a vast network of shoal-water channels and marsh land. Nearly all these channels are bordered with large quantities of driftwood. Still higher up the delta small poplars are scattered in patches among and behind, or inland from, the willows. Some miles up from the lake, where the banks rise about 3 feet above the water, spruce comes in with poplar. There is, however, no relief beyond the increase of a few inches or eet in the elevation of the shore above water. With this slight elevation cut banks appear, together with the slumping of trees and sections of the bank into the river.

Along the Sawmill branch of the delta willows and alders make a solid wall of low, overhanging brush. The banks under these show great numbers of ogs projecting from the silts, as noted by McConnell.[1]

Above the delta the banks rise to an average height of 7 or 8 feet above the ordinary midsummer stage of the river, and 10 or 15 feet is not unusual. The banks are nearly everywhere of fine silt. The following is a representative section taken several miles above the delta:

Soil and peaty material	1 foot
Silt and dark bands of organic matter in alternating bands	4 feet
Fine gray silt	7 feet

Cut banks are found everywhere on one side or on both sides. These retreat rapidly during the warm season. A trapper's cabin was observed at one point partially undermined by the sapping of

[1] *Canada Geol. Surv., Ann. Rept.*, IV, 1888–89 (1890), p. 66 D.

the river. The spruce timber is found caving into the river along considerable stretches. Where a strong current sets against the bank caving proceeds as rapidly as the face of the cut bank thaws. The heavy mat of moss and vegetable matter prevents thawing downward beyond a couple of feet, or less in most sections. The lateral thawing on the face of cut banks results in overhanging masses of silt covered with forest trees (Fig. 3). These finally break off from the bank as thawing and undercutting proceeds, and the slumping frequently splits the trunks of trees, leaving half of

FIG. 3.—Destructive river work on the outside of a curve, lower Slave River

stump on shore. Islands are formed quickly, and many of them disappear quickly. A sandbar first appears; then a multitude of willows spring up. If ice and floods are not too devastating during the next seasons, the small willows persist and materially aid in adding more sediment to the bar.

The building of silt islands below places of maximum cutting, or opposite cut banks on the inside of the curve which results from their development, is seen throughout the course of the Slave River below Fort Smith. These islands, if near one bank, are likely to have successive zones of sediment added to them on the side next the channel with the lesser current, until it is closed and they become

a part of the mainland. All stages of these islands may be observed, from the sandbar just emerging from the water, with no trace of vegetation, to the island with a mature forest of large spruce. As soon as a bar island is built sufficiently above low-water stages for any vegetation to survive on it, a dense growth of willows covers it. These for some years practically exclude other kinds of trees. Their enormously long roots form a network which protects the loose silty material of the young island from destruction by high water, while their twigs and stems greatly accelerate the accumulation of sediment by checking the velocity of the current around

FIG. 4.—Constructive river work on the inside of a curve. Note three successive growths of willows in front of the tall spruce timber representing periodic increments of silt bands to the river bank.

them. The growth of the silt island is therefore rapid after the first growth of willows has become well established. When the island has been built sufficiently high by the annual accretion of sediment, poplars and later spruce begin to displace the willows. Frequently three or more zones may be distinguished around these islands, each a year or more younger than the one inside it, by the height of the willows on them (Fig. 4).

Above the mouth of Slave River for about 125 miles cut banks of yellow sand 15 to 18 feet high are common for long stretches. They terminate abruptly against the ordinary alluvial banks and evidently represent a different and earlier set of deposits which probably are of lacustrine origin. Immediately below the Grand

Detour cut banks of this yellowish sand and gravel 40 feet high are exposed.

The outermost island at the west end of the Grand Detour illustrates the lateral migration of islands which is sometimes observed. The western border is a recent sandbar formed during the present year. Inside this border is a crescent of willows one year old, while the third zone is a very narrow belt of willows nearly mature. The eastern and oldest part of the island is covered with poplars. This east side, however, is a cut bank and is being removed apparently at the same rate at which the western shore is being built up. On the north half of the Grand Detour the cutting is all on the outside bank, but this is not true of the south half, where islands in the channel deflect the current to the inside of the bow, where it now appears to be doing the maximum amount of cutting in beds of buff sand toward the upper end of the bow.

Near Fort Smith the sandbanks of the river reach their maximum height. At the steamer landing at Fort Smith the top of the bluff is 125 feet above the level of the late-summer stage of the water. The base of the section is a bed of thinly laminated gray clay 6 feet thick with numerous concretions which have the appearance of being built up of a series of disks each smaller than the preceding. Above this laminated clay the beds appear to be composed entirely of sand.

For 16 miles above Fort Smith the Slave River flows over a series of granite ledges and between numerous low, rounded, granite islands which interrupt navigation. Above this series of rapids most of the islands are composed either partially or exclusively of granite or limestone instead of silts as in the lower Slave. Above the Stony Islands, where the granite islands rise to a maximum of more than 100 feet above the river, numerous low, granite bosses also rise at intervals a few feet above the water surface, in many cases only a foot or two above low-water stage. Some of them are only 10 to 20 feet in length. Groups of half a dozen or more of these small granite islands are seen in a distance of 200 yards up and down stream. These granite knobs are the nuclei of the many long alluvial islands seen in this part of the river. Frequently a pile of driftwood caps the top of one of the low granite knobs

(Fig. 5). Such a drift pile checks the current and furnishes the beginning of the conditions essential to island formation. The river makes a deposit of silt below it, and this, in time, may connect with another similarly formed island by downstream growth. These low knobs prevail up to the mouth of the main outlet of the Peace. Above the mouth of the Peace the knobs of granite increase in elevation till 25 feet is an average height. Still higher up the Slave River the granite knobs increase in height toward Little Lake and Lake Athabasca, just north, until an elevation of 150 feet or more is reached. In Peace River the same type of island construction and destruction which characterizes the lower Slave is seen.

FIG. 5.—Island composed of drift timber, Slave River

Great numbers of spruce trees are being undermined constantly and thrown into the river. This timber from the cut banks of the Peace and Slave is the source of the enormous quantities of drift logs which line the shores of Great Slave Lake (Fig. 3). Some of the logs accumulate on the low, granite-island knobs and form islands, some of which appear, at high water, to consist exclusively of logs (Fig. 5). Trees whose roots are heavily loaded with earth and stones often strand in shoal water and form the nuclei of new islands.

The delta of Athabasca River near the western end of Athabasca Lake is very similar to that of Slave River in Great Slave Lake. The lake water in front of it is only 2 to 4 feet deep for a considerable distance except along a narrow, crooked channel. The banks rise above the river (late-summer stage) less than 1 foot for 3 or 4 miles. Higher up from the lake they rise gradually to about 3

feet, when willows become common. Ten miles above the river mouth the banks rise to 5 or 6 feet, and large willows and alders are common, but no spruce trees or other evergreens are seen. The banks of alluvium increase gradually in height till at the old Fort Forks at the head of the delta they rise 10 or 12 feet above low water.

Numerous good examples occur in the lower part of the Athabasca, in the cut banks, of tree stumps which have been buried where they grew under from 2 to 6 feet of alluvium by the shifting of the course of the river. They are illustrated by one of E. T. Seaton's figures.[1] O'Neill[2] has described similar examples of alluvium-buried forest beds in the delta of the Mackenzie where the buried stumps are much larger in girth than any other trees now growing in the delta. The testimony of the land surveyors who have run their lines across an extensive region between the lower Peace and Athabasca rivers indicates that with the exception of two or three localities bedrock outcrops are wanting over a vast area between these two rivers, an area which is doubtless underlain throughout by fluvial and lacustrine deposits.

About 15 miles above the Old Fort forks the river cuts into a sand bluff 75 or 80 feet high. The heavy load of sand acquired by the river at this and other points higher up results in extensive sandbars which are spread over the middle of the river and interfere with steamer navigation at low water. About 3 miles below Point Brule the extensive alluvial and lacustrine deposits are terminated on the east side of the river by land rising 200 feet or more above it.

CONTRASTING FEATURES OF THE MACKENZIE RIVER

The bowlder pavements are among the most striking features of the Mackenzie River. These marvelous pavements, resembling cobblestone roadways, often stretch along both banks of the great river without interruption for miles (Fig. 6). They frequently extend up the concave banks from below low water to a height of 25 feet or more above it. The shores of many of the islands as well as the banks of the river are paved with bowlders. On the Slave, lower Peace, and lower Athabasca rivers the pavements are entirely

[1] *The Arctic Prairies*, p. 197. Charles Scribner's Sons (1911).

[2] *Canada Geol. Surv., Sum. Rept.* (1915), p. 239.

absent. The channels of these streams are cut in lake and river silts which contain no bowlders, while the channel of the upper Mackenzie is cut for the most part in glacial till containing an abundance of bowlders, which through the grinding and sliding of the ice during the spring break-up are pressed deeply into the clay and built into pavements.

The contrast between the bowlder-paved banks of the Mackenzie and the bowlder-free banks of the rivers just mentioned is related to another feature in which the Mackenzie contrasts sharply with these rivers in the bowlder-free silts. The latter meander widely, while the former pursues a fairly direct course, its bends showing none of the characteristics of typical meandering streams.

FIG. 6.—Bowlder pavement on island opposite Old Fort Wrigley, Mackenzie River.

The Grand Detour on the lower Slave is an example of the meanders of this stream and the lower Peace. At the Grand Detour the Slave swings abruptly to the westward in a great loop of about 20 miles. The distance across the base of this meander is only one mile. The relatively direct course of the Mackenzie as compared with the meandering lower Slave and Peace rivers can be explained, in part at least, by the protection which the bowlder pavements afford against lateral cutting. These pavements furnish protection against erosion of the banks as effective as artificial riprap, and thus prevent the excessive cutting at the bends which in many streams leads to the formation of loops and oxbows.

The plowing and gouging action of ice is nearly everywhere in evidence along the Mackenzie. At the head of the river, in the shallow eastern channel, one can see through the clear water numerous deep grooves made by ice cakes or bowlders pushed by ice in the bowlder clay of the bottom. In the gravel or silts of low islands the broad grooves made by ice-shoved bowlders or ice blocks can often be traced for a considerable distance (Fig. 7). In some localities the plowing and scooping action of the ice carries large quantities of mud from the bottom to the banks of the river (Fig. 8).

FIG. 7.—Trail left by ice-shoved bowlder or ice cake. Note the cratic course unlike that left by drifted tree roots, Mackenzie River.

The upstream ends of some of the low islands are built up in this way several feet higher than the rest of the island. In such cases the ice is likely to build a clay dike across the head of the island at right angles to the course of the river terminating at the top in a sharp ridge. The front of such a dike is frequently bowlder-paved and thus becomes almost as resistant to river erosion as a hard rock cliff (Fig. 9).

A feature of the ice work along the banks of the Mackenzie is the distribution of great numbers of a small bivalve, *Sphaerium vermontanum*, over the higher levels of the bank, much higher than the ordinary stages of the river in summer could carry them. I

have never seen this shell in the shallow water of the river, although other shells are common there. It appears, therefore, that it lives

FIG. 8.—River bottom clay and silt shoved on bank of an island by ice scour, Mackenzie River.

abundantly in the deeper parts of the river and reaches the localities where found on the banks as a result of ice excavation and the vagaries of strong current action and transportation during the

FIG. 9.—A clay island protected from erosion by a bowlder pavement

spring break-up. When the ice breaks on the river in the spring, ice jams occur which raise the river to abnormal heights at various localities. McConnell[1] has given the following striking descrip-

[1] *Geol. Surv. of Canada, Ann. Rept.*, IV, 1888–89 (1890), p. 87 D.

tion of this phenomenon as observed by him at the mouth of the Liard:

> Huge cakes of ice under the enormous pressure were constantly raising themselves on end and falling, and the whole mass, urged forward by the terrible energy of the piled-up waters behind, was battering a way across the Mackenzie. The ice of the latter, fully five feet thick and firm and solid as in midwinter, was cut through like cardboard, and in a few moments two lanes were formed across its entire width, while a third was open for some distance below, before the force of the rush was exhausted and the movement ceased. In the afternoon the crashing of trees in a channel behind the island, concealed from view by the intervening forest, was distinctly heard and showed that a temporary vent had been found there, and in front of the fort intermittent fountains played at intervals from holes and crevices in the ice. At midnight

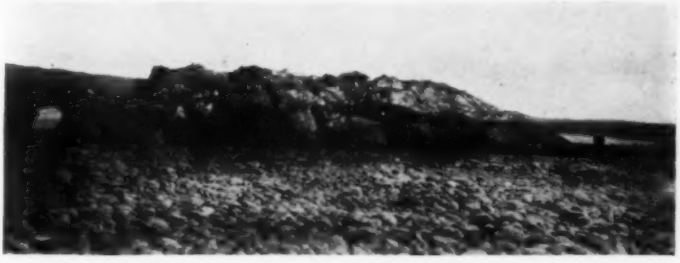

FIG. 10.—A remnant of a mass of river-shoved ice and the bowlder pavement which such ice levels and smoothes, Mackenzie River 15 miles above Fort Wrigley.

> the dam at the mouth of the Liard gave way and the massive crystal structure was hurled by the liquid energy behind it against the firm ice in front with such force that the whole sheet, for some miles below the fort, was crushed into fragments by the impetuosity of the assault.

At the Ramparts ice jams are reported to have sometimes raised the river nearly 100 feet.

About 15 miles above Fort Wrigley, I observed the remnants of one of these ice jams—an accumulation of great ice blocks which had remained unmelted as late as July 22 (Fig. 10). At this date the principal mass of ice blocks had a thickness of 25 feet. They were covered with a thin veneer of dark mud, and hundreds of specimens of *Sphaerium vermontanum* were scattered over their surface.

Good examples of rock basins which represent apparently one phase of the work done by river ice occur on the limestone island opposite old Fort Wrigley. A considerable area of limestone beds lying approximately horizontal on the northeastern side of the island is covered by the river during the spring break-up, but exposed through the summer. On this area a group of four rock basins has been developed in the limestone. The rim of the largest of these rises from 5 to 10 feet above the bottom. This basin has a maximum length of 65 feet and a width of 30 feet (Fig. 11). Another of these basins has a diameter of 10 feet and a depth of 5

FIG. 11.—A rock basin in limestone between low and high water, Old Fort Wrigley, Mackenzie River.

feet. The basins appear to be the product of the plucking action of the river ice which covers them during the late winter stages of the river.

LAKE FILLING

Two large lakes, Athabasca and Great Slave, lie in the path of the Mackenzie-Athabasca drainage system. Great Slave Lake, much the larger of the two, has a length of about 290 miles from east to west. A recent survey of part of the north shore by A. E. Cameron, of the Canadian Geological Survey, changes the rank in size of Great Slave Lake from fifth to fourth among the great lakes of the continent. As pointed out by McConnell,[1] it seems originally to have had "the form of a great cross with one arm

[1] *Geol. Surv. of Canada, Ann. Rept.*, IV, 1888–89 (1890), p. 65 D.

penetrating the crystalline schists while two others stretched north and south along the junction of these with the newer sedimentaries, and the fourth extended itself over the flat-lying Devonian to the west." Lake Athabasca lies almost entirely within the limits of the pre-Cambrian rocks.

Inspection of the map (Fig. 1) will show that the drainage of an enormous area in Northwestern Canada, extending from the interior of the Rocky Mountains region far into the pre-Cambrian area west of Hudson Bay, passes through Lake Athabasca and Great Slave Lake. Practically all of the vast quantity of sediment which is annually stripped from this extensive area is left in these great settling basins. A noteworthy feature of this lacustrine sedimentation is the extreme inequality of its distribution. Probably 95 per cent of the immense volume of sediment which enters Great Slave Lake is poured into the south side of the lake. The streams entering the north side of the lake are nearly all small and comparatively insignificant. In the course of a survey of the north shore of the west arm of Great Slave Lake, A. E. Cameron found that "throughout the entire 136 miles of shore line between the Mackenzie River and the north arm only one stream, and it a very minor one, was found entering the lake" (manuscript). The streams which do enter the north shore of the lake lose most of their sediment in passing through small lakes before reaching Great Slave Lake. On the south shore, besides the Slave, which is one of the great sediment-bearing streams of the continent, three other rivers enter, each of which has a considerable volume. These are the Taltson, the Buffalo, and the Hay. It is the zone of lake bottom bordering the 150 miles of the south shore receiving these streams which takes the great bulk of the river-borne sediment. Great Slave Lake opposite the mouth of Slave River, which carries the great bulk of the silts entering the lake, has a width of more than 60 miles. Little or none of the sediment brought in by the Slave has any chance of being deposited in the northern half of the lake. Coastwise currents, however, distribute the silts from the Slave and other south-shore streams widely along the south-shore bottom zone. It is probable that along the shore line between the Hay and the Buffalo rivers the prevailing direction of the coastwise

currents is easterly. This was evidently the case off the mouth of the Buffalo when I passed it early in July. The canoe entered muddy water some distance east of the mouth of the stream, but entered clear water immediately west of the west bank of the river, although a breeze from the northeast was blowing at the time. At a later date Mr. Cameron made similar observations at the mouth of the Buffalo. The muddy water of the Slave ceases to be noticeable in the lake 10 or 12 miles west of the western side of the delta.

There is probably no lake in North America which receives anything like the amount of driftwood which is poured into Great Slave Lake, chiefly through the Slave River (Fig. 12). The shores

FIG. 12.—Drift timber on the shore of Great Slave Lake

are nearly everywhere lined with enormous quantities of logs, many of which came from a thousand miles or more up the Peace. Large quantities of this driftwood must eventually become water-logged and sink. Practically none of it leaves the lake by the Mackenzie. At some localities the drift timber is intimately mixed with the shingle of the beaches (Fig. 13).

In Lake Athabasca sedimentation appears to be even more localized than in Great Slave Lake. The maximum length of Lake Athabasca, which nearly equals that of Lake Ontario, lies in an east and west direction. The great bulk of the sediment which the lake receives is poured into the western end by the Athabasca and Peace rivers. It is discharged from this end by way of Little Lake and Slave River. The relationship of the Peace River discharge to Lake Athabasca is peculiar and variable. Three or four

outlet channels of the Peace empty directly into Slave River, but the Quatre Fourches channel, which branches off above the Slave River outlets, empties into Lake Athabasca. Ordinarily by far the greater part of the Peace River water flows directly to Slave Lake via Slave River; but a conjunction of low water in Lake Athabasca and high water in the Peace River may for a time reverse the direction of flow in the upper Slave River and turn all of the Peace River outflow into Lake Athabasca. Such a reversal of drainage involves the temporary obliteration and reversal of Little Rapid, located about 25 miles north of Lake Athabasca in Slave River. Father Lafebre, of the Catholic Mission, informs me

FIG. 13.—A double beach of shingle and drift wood, shore of Great Slave Lake

that he has observed this reversal in May. It thus appears that at times the whole of the combined volume of sediment carried by the Peace and the Athabasca is dumped into Lake Athabasca. When this reversal of current near the head of the Slave River occurs, it is evident that the deposition of sediments must proceed in the western part of Lake Athabasca at an enormously increased rate. Under these special conditions the whole of the Peace River sediment, nearly all of which ordinarily reaches Great Slave Lake, stops in Lake Athabasca. During the unusual seasons when the Peace River contributes largely to the Lake Athabasca sediments, the annual layers of silt would not only be thicker than those ordinarily laid down but would also probably have a much greater easterly extension.

Lakes Mamawa and Clair, lying west of Athabasca Lake, appear to represent parts of a former greater Lake Athabasca which have been segregated into separate lakes by lake filling. Lake Clair has a shore line approximating 200 miles in length. Its depth is reported seldom to exceed 8 feet. Little Lake, through which the outflow of Lake Athabasca passes, is extremely shallow except for a channel through which most of the outflow passes to Slave River. East of this channel a large area on the north side of the lake is completely silted up. On the west side large areas of aquatic plants and stranded logs indicate the approach of the final stage and extinction of the lake.

Observations made on the relative clarity of the Slave River water above and below the mouths of the Peace show but a slight difference in the clarity of the water. This would indicate that the river water passes through the narrow western part of Lake Athabasca too quickly to lose nearly all of its sediment.

NOTES ON THE MISSISSIPPIAN CHERT OF THE ST. LOUIS AREA

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The origin of chert is a question which is still open to discussion. Although several of the chert series of Europe have been studied somewhat in detail by a number of geologists,[1] among the more important Hull and Hardman, Hinde, Sollas, Renard, and Cayeux, the conclusions reached with regard to the origin of chert have been considerably at variance. In this country Lawson and Palache seem to have demonstrated the organic (radiolarian) origin of certain Californian cherts. The Missouri cherts, chiefly Mississippian, and some of the closely associated cherts of neighboring states have been studied, although not in detail, by Shepard, Ball and Smith, and Van Tuyl, and, in thin section only, by Hovey. The conclusions as to the origin of the chert have not been in agreement. The present paper presents the results of a detailed study of the Mississippian cherts of the St. Louis area both in the field and in thin sections.

OCCURRENCE OF THE MISSISSIPPIAN CHERT OF THE ST. LOUIS AREA

The Mississippian chert of the St. Louis area is found in the St. Louis and in the Burlington-Keokuk limestones, to a slight extent in the Warsaw shales, and in very rare, small patches in the

[1] E. Hull and E. T. Hardman, *Trans. Royal Soc., Dublin*, I (1878), 71. G. J. Hinde, *Geol. Mag.* (III), IV (1887), 435–46. W. J. Sollas, *Am. Mag. Nat. Hist.* (5), VI (1880); VII (1881); *Proc. Roy. Soc., Dublin*, VI (1887), Part 11. A. F. Renard, *Bull. Acad. Roy. Belgique* (2), XLVI (1878), 471. L. Cayeux, *Ass. franç. pour l'avanc. de Sci.* (Carthage, 1906), pp. 220–93. A. C. Lawson and C. Palache, *Bull. Geol. Dept. U. of Cal.*, II (1902), 354–65. E. M. Shepard, *U.S. Geol. Surv., W.S. Paper 195* (1907), p. 19. T. M. Van Tuyl, *Proc. Iowa Acad. of Sci.*, XIX (1912), 173–74. E. O. Hovey, *Mo. Geol. Surv.*, VII, Part II (1894), pp. 727–39.

Salem limestone. The stratigraphic position of the chert beds is shown in the accompanying generalized section of the St. Louis area (Fig. 1). The Burlington-Keokuk limestone wherever exposed

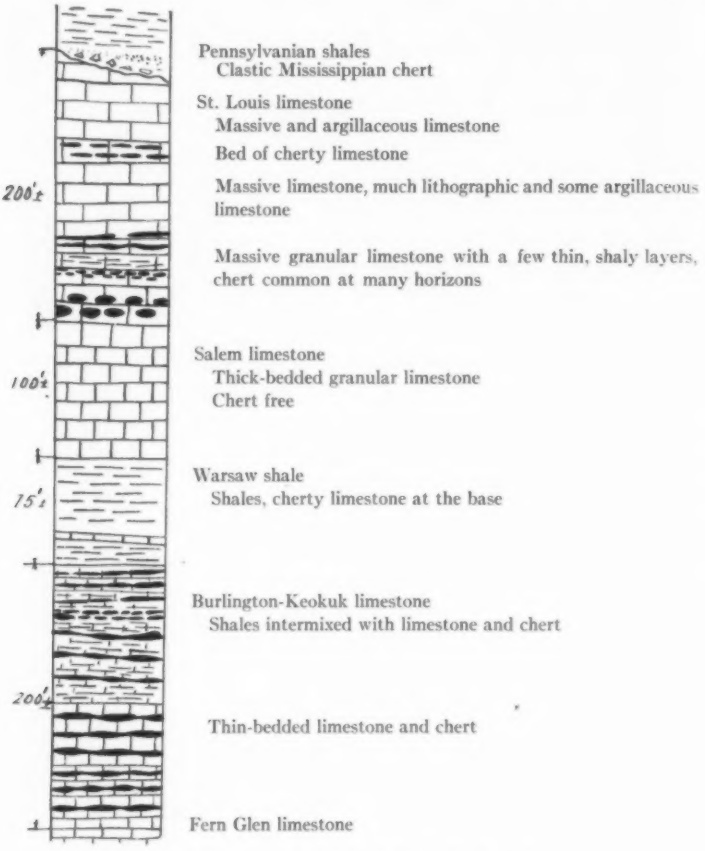

FIG. 1.—Generalized section of the St. Louis region

in this area is consistently very cherty. The amount of chert in the St. Louis limestone varies considerably from place to place. The presence of more or less chert at the base is characteristic, but it

was impossible to correlate with certainty throughout the area the higher cherty horizons.

MORPHOLOGY OF THE CHERT BEDS

The general form of the chert varies considerably from bed to bed, although it seems to be more or less constant for any individual horizon. It is possible to distinguish several distinct types of occurrence of the chert. Most of the chert in the Burlington-Keokuk limestone and some of the chert in the St. Louis limestone are in nodular bands or bands of flattened nodules. The nodules are irregularly elliptical with horizontal diameters subequal and one and a half to twice the vertical diameter, and are seldom less than three centimeters or more than ten centimeters in diameter vertically. The nodules are rounded and usually sharply delimited, at least to megascopic examination, from the inclosing limestone. In any given chert bed these nodules show distinct distribution parallel to the stratification and by coalescence form the nodular bands intercalated between the thin limestone beds. In a few chert beds in the Burlington-Keokuk the chert is irregularly ramifying, with angular outlines, and in general pattern resembles some of the mottled Ordovician limestones. Although the chert of this type usually crosses many distinct layers of the limestone, the greatest development shows distinct distribution parallel to the stratification. A form of the chert very characteristic of the St. Louis limestone and found but very rarely in the Burlington-Keokuk are the bands of nodules, spherical or ovoid in shape and six to sixty centimeters in diameter. The contact of the nodule and the limestone is apparently sharp, but there is usually present a thin chalky-looking transition zone. The nodules in a given band characteristically are well aligned to some horizon, in many cases the middle of a thick limestone bed. A form of the chert that is found both in the St. Louis limestone and in the Burlington-Keokuk limestone is a thin band, pancake-like in the St. Louis and platelike in the Burlington-Keokuk. These bands most commonly are six to ten centimeters thick, but in some cases much more, and fifteen to fifty meters long. The contact of the chert of these bands with the limestone seems to be sharp.

LITHOLOGICAL CHARACTER OF THE CHERT

To the naked eye the chert characteristically appears stony, but in some cases granular or chalky, although in the latter cases the chert is not appreciably less tough or hard. In color the chert varies from dirty white to dark gray and, except for one thin band of chalcedonic chert, is mottled and banded. The mottling is similar in effect to that given by the grain to the limestone and is apparently a pseudomorphic character of the chert reflecting the granular character of the limestone. The banding is concentric with the form of the nodule, or horizontal. In the latter case it is a retention of the stratification markings. The chert with rare exceptions is fossiliferous wherever the limestone of that horizon is fossiliferous. Crinoid stems are by far the most common fossil. Bryozoa, Spiriferi, Producti, and other brachiopods, Lithostrotion in the St. Louis limestone and Fusulina are also common. A notable feature about the fossils is that in a very great number of cases they are still calcareous and do not show the effects of the siliceous replacements of the rest of the rock.

In thin section under the microscope the chert is seen to be composed chiefly of quartz with more or less calcite, and in some cases with chalcedony, opal, dolomite, pyrite, and iron staining. The quartz making up the mass of the chert is in excessively fine grains, less than 0.01 mm. in diameter, which are not clearly distinguished even under the high power, and it is to the compensation due to the superposition of these small grains that many of the areas dark under crossed nicols are to be attributed. Locally, in many cases within a shell, there are patches of allotromorphic grains of larger size (0.1 mm.). In a few thin sections there were seen larger, subangular, clastic grains. The calcite, abundant through much of the chert, is in small rounded grains that cloud certain areas or form patchy aggregates through the chert, or is in large grains forming the unreplaced shells. The calcedony, when present, is in thin, fibrous, wavy bands that permeate part of the chert, lining shells, and microscopic cavities. The presence of the opal is inferred from the presence in part of the chert of much isotropic material with a moderately low index of refraction. The dolomite, where observed, was in small rhombs scattered through the chert and was distinctly

more abundant in the chert than in the surrounding limestone. Pyrite was present in only a few cases and was in small cubes in the center of quartz-filled cavities. In much of the chert there is a slight amount of iron staining present.

The structure of the chert as revealed under the microscope varies considerably. Part of the chert is massively composed of very fine grains, whose boundaries cannot be made out. Much of the chert is similarly composed in large part, with ramifying, banded microscopic masses of calcedonic material or interlocking quartz grains, which seemed to have filled pre-existing cavities. The interior cavities of shells are in most cases filled with interlocking quartz grains. The shells, even very minute ones, for the most part are composed of calcite in medium-sized grains, but in some cases show partial or complete replacement. Where replacement of a shell has taken place it is mostly by fine allotriomorphic quartz granules. Concentric banding is shown by much of the chert and is caused in some cases by very slight differences in the amount of staining, probably ferruginous, and in other cases by a variation in the amount of admixed calcite grains, the calcite rich areas tending to a chalky white color. In a chert much resembling in marking the mottled Ordovician limestones the mottling is likewise due to a rapid variation of the proportions of calcite to quartz grains. Banding due to stratification is present in some of the chert and is shown by the orientation of minute shells, by variation in the amounts of a cloud of fine black specks, and by variation in the staining.

RELATION OF CHERT TO SURROUNDING LIMESTONE

The character of the contact of the chert and the limestone apparently varies with the different chert beds. In many cases there is a visible transition extending over a zone of one to two centimeters. This is particularly the case with the spherical nodules of the St. Louis (Fig. 2). But the contact more commonly is sharp, at least under megascopic examination. In the Osage chert of Iowa such contacts are reported by Van Tuyl microscopically to show gradual transition. In the thin sections of St. Louis

chert examined the transition was distinctly sharp, being confined to a zone of 0.2 to 0.4 millemeters in width.

The lateral contacts of the larger, semispherical nodules can be seen in many cases to be zones of slight displacement. The lines of stratification running into or across the chert are broken and slightly displaced upward, the more so toward the top of the nodule, and not at all or only faintly in reverse at the base. The ends of the line of stratification in the adjoining limestone in many cases

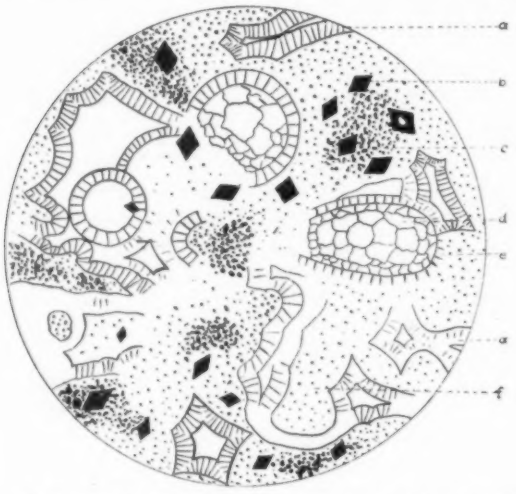

FIG. 2.—Chert from the St. Louis limestone, St. Louis, Missouri, under the high power: *a*, chalcedony; *b*, dolomite rhombs; *c*, limonite stain; *d*, granular quartz; *e*, silicified shell; *f*, microgranular groundmass.

are bent up near the nodule with the upper ones arching over, but in other cases run to the contact without deviation. Slickensides were found in a very few cases on the lateral contacts, showing relative movement upward of the chert of the nodule.

CHARACTER OF THE ROCK INCLOSING THE CHERT

Although chert is confined to calcareous rocks, the exact character of the rock in which chert appears varies widely. The grain seems to have no effect on the presence of chert, which is found

indifferently in fine-grained, even lithographic limestones, and in coarse-grained ones. It is found in massively bedded as well as in thin-bedded limestones. It is not found, to the writer's knowledge, in pure or only slightly calcareous sandstones or shales, but is found in arenaceous and argillaceous limestones. It is found in highly magnesium limestones and in very pure limestones. A series of analyses of the chert-bearing St. Louis and Burlington-Keokuk limestones at St. Louis show a variation in composition as given in Table I.

TABLE I*

Limestone	Insoluble Siliceous Residue	Combined Oxides	$CaCO_3$	$MgCO_3$
St. Louis	1.48–9.56	0.35–1.82	61.88–94.97	0.94–24.53
Burlington-Keokuk	1.10–4.35	0.40–1.82	77.95–94.50	3.18–14.84

*Analyses by A. E. Atwood, *Geol. Surv. of Missouri, Bull. No. 3* (1890), p. 77.

CONTEMPORANEOUS CHERT OF OTHER AREAS

In areal distribution these Mississippian cherts are not restricted to the St. Louis area, but are widespread and are characteristic of the St. Louis limestone and equivalent formations and the Burlington-Keokuk limestone and equivalent formations practically wherever they are found. The Salem limestone of the St. Louis area is free from chert, as is also the Bedford oölite, its equivalent to the east. The exact extent of the distribution of the chert in the St. Louis limestone and the Burlington-Keokuk limestone is best shown graphically in Figs. 3 and 4, on which are plotted the outcrops of these formations and the areas in which they are chert-bearing. The correlation of formations on these maps is taken largely from B. Willis' "Index to the Stratigraphy of North America," *U.S. Geol. Surv. Prof. Paper 71*. While the morphology of these equivalent chert beds varies somewhat from locality to locality, yet there seems to be a greater or smaller constancy of habits of the chert of each formation. The St. Louis is characterized by even, ball-like chert even to Alabama, while the Lauderdale is spoken of as platelike, and the Boone chert and Grand Falls chert of western Missouri are said to be lenslike or sheetlike. It is perhaps worthy

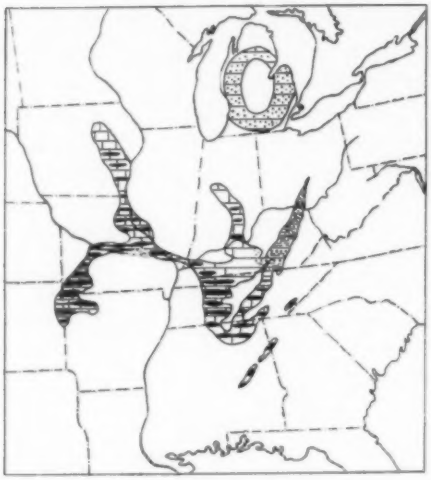

FIG. 3.—Distribution of the chert in the Burlington-Keokuk limestone and equivalent formations.

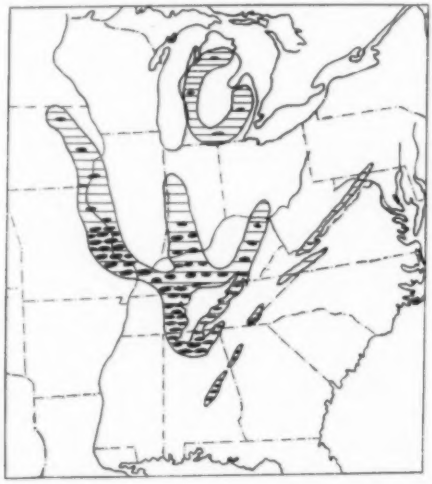

FIG. 4.—Distribution of the chert in the St. Louis limestone and equivalent formations.

of note, although very possibly nothing more than a coincidence, that much chert is found in the lower Carboniferous limestones of England, Ireland, and Belgium.

AGE OF CHERT

In age the chert of the Mississippian of the St. Louis seems without doubt to lie between the early Pennsylvanian and the time of formation of the chert-bearing limestones. The evidence of the pre-Pennsylvanian age of the chert lies in the presence of the Mississippian chert as clastic fragments in the base of the Pennsylvanian. In a Missouri-Pacific railroad cut between Kirkwood and Barrett's Station, St. Louis County, Missouri, and also in a Frisco railroad cut a half-mile east of Meramec Highlands, clastic chert carrying Lithostrotion proliferens and Spirifer Keokuk and showing predepositional weathering is to be found in abundance at the base of the Pennsylvanian shales. In Miller County, Missouri, clastic chert from the Burlington limestone is reported as being present in the Graydon sandstones and the Coal Measures shales. In the Joplin district likewise clastic Burlington chert is reported as lying at the base of the Pennsylvanian.

The evidences of the formation of the chert later than the formation of the containing limestone are several. The replacement of fossils has been cited and probably in some cases correctly so. Although the fossils in the great number of cases have not been replaced, the replacement of the fossils, especially the larger ones, when studied in their sections under a microscope seems, partly at least, surely to have taken place after the formation of the chert. The retention in the chert of the markings of the limestone, including the grain, stratification, styolithes, and fossiliferous character, is valid evidence of the secondary character of the chert. The mottling of the chert in very many cases accurately reproduces the appearance of the granular character of the limestone. The stratification markings and the variation in grain and fossil content in the different layers can in many cases be traced into or across the chert. The arching of the stratification and the faulting and slickensiding at the contacts of the nodules are also evidences of the secondary character of the chert. The stratification of the limestone in which

the pancake-like chert bands appear, for example, is more or less contorted, although in the closely associated, chert-free beds it is even and regular. The slight vertical displacement in the slickensides that are found at the lateral contacts of some of the larger nodules has already been mentioned.

Yet while the chert seems definitely to be secondary, there is an aspect on its part of contemporaneity with the limestone. This is evidenced by the widespread development of the chert in the St. Louis limestone and in the Burlington-Keokuk limestone, although the intervening Salem limestone—Bedford oölite limestone—is practically chert-free. The constancy of habit of the chert in the St. Louis limestone and in the Burlington-Keokuk, respectively, over a wide area has already been noted. The development of the chert also is parallel to the stratification. In a band of isolated nodules there is characteristically a striking alignment of the nodules at some level in a bed, often a massive one. There are in some cases several bands, and in a few cases there is no alignment of the nodules, but where the bands are present they are parallel to the stratification. The nodule-containing bed is in some cases three or four feet thick, with no shale partings, is uniform in grain and character throughout, and shows no apparent cause for percolating waters, whether silica-bearing or not, to flow at certain definite and localized levels. The pancake-like chert masses and the chert lenses likewise show conformity to stratification, although in this latter case there is in many places coalescence of several lenses by lateral thickening. As far as could be seen there was no possibility of localization of the chert at definite levels by control of percolating waters by shale partings or such. If the chert were purely epigenetic, it would seem probable that the chert bands would show some tendency to cut across the stratification.

The various theories that have been proposed to explain the origin of chert may be said in essence to be six.

I. The silica is of organic origin, derived chiefly from the spicules of siliceous sponges. The silica may be derived from other of the siliceous organisms, as, for instance, in the case of the radiolarian cherts of California.

1. The chert is supposed to be derived from colloidal silica which formed from the decomposition of siliceous sponges and collected in the depressions of the sea floor. The chert bands are supposed to represent former sponge beds, where the sponge remained accumulated in place over a considerable area.

2. The chert is supposed to form before consolidation of the limestone through the solution of scattered siliceous spicules and the almost immediate replacement of parts of the limestone.

3. The chert is supposed to form after the consolidation of the limestone through the solution by percolating waters of the siliceous spicules and the replacement of part of the limestone by this dissolved silica.

II. The silica is supposed to be of inorganic origin.

4. The chert is supposed to form by the precipitation of silica and the replacement of the limestone in the presence of circulating waters which have passed through sandstones, arenaceous rocks, or rocks containing silicates.

5. The chert is supposed to result from the reaction of the dissolved silica of sea-water with the limestones, with the consequent precipitation of the silica and with possibly a later concentration.

6. The chert results from the diffusion of silica in solution through a limestone. The concentration will vary in the direction of the diffusion, and the deposition resulting when the concentration is sufficient will be in zones perpendicular to the direction of diffusion. As the conditions for diffusion are more favorable in the early days of the consolidation and as the most likely direction for the diffusion is upward toward the surface or downward from it, the deposition will be parallel to the stratification, although independent of it. The development of the chert in successive zones is due to the lowering of the concentration immediately around the first started zone or zones of crystalizing material. The silica may be derived from organic or inorganic sources.

ORIGIN OF THE CHERT OF THE ST. LOUIS AREA

The source of the silica of the chert of the St. Louis area is not as clear as in the cases of the English cherts and flints, the radiolarian cherts of California, and the cretaceous cherts of Texas, and

apparently must remain a matter of conjecture. Evidence of an organic origin is wanting. In slides of the St. Louis chert spicules were present only in one case. In his study of slides of the Missouri cherts Hovey reports that he found only one carrying sponge spicules. Likewise Van Tuyl in his study of the cherts of the Osage series found sponge spicules present in only one sample. Of the presence in numbers in the Mississippian seas of other silica-secreting organisms nothing is known.

In the case of the cherts of the St. Louis area the theory that the chert is formed from the collection of colloidal silica on the sea floor is not applicable, since the chert is plainly secondary. Hinde's application of this theory to explain the presence of unsilicified shells in the chert is not necessary, as the differential replacement is readily accounted for by the lower solubility of the shell material. In this connection a brief series of tests was run on the relative solubility of recent and fossil pelecypod shells, fossil brachiopod shells, on crinoid stems, and on chert-bearing and chert-free limestone. The material was powdered to pass through a two-hundred-mesh sieve and was digested in 25 cubic centimeters one-half normal HCl, plus 350 cubic centimeters distilled water, and the time required for neutralization, as shown by methol orange, was noted. A marked tendency was shown toward less solubility on the part of the shells, crinoidal limestone, and chert-free limestones, such as the Salem, and greater solubility on the part of the limestones associated with chert. The experiments were not extended enough to be conclusive.

That the chert was formed before the consolidation of the limestone from silica derived from the solution of siliceous spicules or tests is possible in the case of some of the chert. But it is definitely not possible in the case of most of the chert, as the chert did not form until after the limestone had acquired its granular character. The formation of the chert in a similar manner during, or later than, the consolidation is more possible. The chert is secondary and is pre-Pennsylvanian, and therefore must have formed during, or not long after, the consolidation of the limestone. There is, however, no positive evidence of the organic origin of the silica. The suggestion that the silica of the chert is exotic and that it has

been introduced from other siliceous formations by the underground circulation, possibly that of the geologic present, does not seem valid. The formation of the chert cannot have taken place through the agency of the present-day circulation, since the presence of the chert at the base of the Pennsylvanian shows the period of formation to have been late Mississippian or early Pennsylvanian. The jasperoid of the Joplin district, furthermore, is a chertlike siliceous deposit that is said to have been deposited by the same underground circulation that is responsible for the mineralization of the region. But the jasperoid is later than the chert and distinctly different. The more serious objection, however, is the conformity of the chert with the stratification. Vertical zones following the joints are not found. The chert is found widespread, but is not found in an adjacent formation and is more or less similar over wide areas, but different in aspect in the different formations.

The derivation of the silica of the chert through precipitation from sea-water is a possibility. Silica is precipitated from solution by calcite and replaces it when H_2CO_3 is present, and, as the accumulating sediments of the ocean bottom usually contain decaying organic matter, H_2CO_3 should be present. A tenth of the yearly increment of saline material in the ocean is silica, but the silica content of sea-water is practically nil; 1 part in 220 to 460 thousand. The very considerable annual increment of silica must therefore be removed quickly, either by direct chemical precipitation or through the action of organic agents. In the case of the Mississippian beds of the St. Louis area it is not known that siliceous organisms were present to any important extent at the place and time of the deposition of the beds. The degree of concentration of the silica in the ocean-water, in connection with the slow rate of diffusion and proximity or distance from the mouth of a river, may be an important factor, contributing to the lack of chert in some limestones, as, for instance, the Salem and Kemmswick limestones. Such chert-free limestones may have formed at a distance from the mouths of rivers, and the silica may have been completely precipitated before currents brought these waters to the place of deposition of these beds.

The principles of diffusion as given by Liebesang and Cole in connection with the origin of flint partially explain some of the features of the chert of the St. Louis area. These principles seemingly explain the formation of the chert after, but not long after, the formation of the limestone—the position of the chert parallel to the stratification but independent of it, the rhythmic deposition of the chert, and the excessive development of the chert within a few hundred feet of a great uncomformity. They are equally applicable whether the silica is derived from organic or inorganic sources, and would seem to necessitate a rather general distribution at the start of siliceous material through the mass. The particular localization at a given horizon of a chert bed might be affected, however, through the influence of a local excess of siliceous material on the concentration at that horizon. The localization might also be affected by the solubility of the limestone of the various horizons. A serious difficulty that would seem to arise in connection with the application of these principles in the present case is the presence of the numerous argillaceous beds. It is difficult to see how much diffusion could take place through these shale beds, and the diffusion would seem necessarily to be confined chiefly to lateral diffusion through the more porous beds.

Editorial

GROVE KARL GILBERT

The passing of Dr. Gilbert after almost seventy-five years of activity deprives geological science of one of its ablest and most honored representatives. It is permitted to few men to leave an equally enviable record. To an unusual degree his work was distinguished by keenness of observation, by depth of penetration, by soundness in induction, and by clarity of exposition. It is doubtful whether the products of any other geologist of our day will escape revision at the hands of future research to a degree equal to the writings of Grove Karl Gilbert. And yet this is not assignable to limitation of field, or to simplicity of phenomena, or to restriction in treatment. The range of his inquiries was wide, his special subjects often embraced intricate phenomena, while his method was acutely analytical and his treatment tended always to bring into declared form the basal principles that underlay the phenomena in hand.

In the literature of our science the laccolith will doubtless always be associated with the name of Gilbert. In its distinctness as a type, in its uniqueness of character, and in the definite place it was given at once by common consent, one may almost fancy a figurative resemblance between the laccolith and its discoverer and expositor. Gilbert's monographs on the Henry Mountains and on Lake Bonneville will long stand as unexcelled models of monographic treatment. His contributions to physiographic evolution, particularly his analysis of the processes that end in base-leveling, link his name with that of Powell, and give to these two close friends a unique place as joint leaders in interpreting morphologic processes. Glacial and hydraulic phenomena were also fields in which Gilbert's powers as an investigator and expositor were signally displayed.

In accuracy of delineation, in clearness of statement, and in grace of diction Gilbert's contributions are certain long to stand

as models of the first order. His personality was of the noblest type; he was a charming companion in the field; he was a trusted counselor in the study. The high place he has held in the esteem of co-workers is quite certain to merge into an even higher permanent place to be accorded him by the mature judgment of the future.

T. C. C.

Petrological Abstracts and Reviews

ALBERT JOHANNSEN

SOSMAN, R. B., and MERWIN, H. E. "Data on the Intrusion Temperature of the Palisade Diabase," *Jour. Wash. Acad. Sci.*, III (1913), 389–95.

Slabs of the underlying Newark shale and arkosic sandstone have in many cases been "floated" up into the igneous rock of the Palisade diabase of New York and New Jersey, apparently while the latter was still liquid. This paper deals with studies made of the comparative fusion points of the diabase and the arkose. The former begins to melt at 1,150° but does not flow till 1,225°, while most of the latter is fused at 1,150°. The inclusions in the Palisade diabase, however, show no trace of fusion, and the authors conclude that the fusion point of the diabase was lowered by mineralizers at the time of the intrusion.

SPETHMANN, HANS. *Islands grösster Vulkan. Die Dyngjufjöll mit der Askja.* Leipzig: Veit & Co., 1913. Pp. 143, figs. 36, bibliography.

The author gives first a summary of work previously done in this region, including an account of von Knebel's ill-fated expedition. He then tells of the development of the maps of this region, describes the forms of relief, the climate, and the vegetable and animal life.

The volcano Dyngjufjöll lies east of the central part of Iceland. Its crater, Askja, is the largest in the island, and has a fairly flat bottom of from 55 to 60 square kilometers. In the southeastern portion of this crater bottom is a lake, Knebel Sea, covering about one-fifth of the area, and at its northeast shore is an active crater, Rudloff Crater. Southwest of the lake is a solfatara field. The mountain owes its origin to volcanic eruptions from a conduit within the area of Askja. The material ejected was fragmental, but later was followed by a lava flow which filled the cauldron with a sea of lava and caused overflows at several points. There were various fluctuations of the surface of this flow, the last one being a sinking of the level from 40 to 50 meters. In January and March, 1855, there were eruptions of fragmental materials, and at the same time several large areas of the crater bottom, near the Knebel Sea, settled and filled with water from this lake.

TYRRELL, G. W. "A Petrographical Sketch of the Carrick Hills, Ayrshire," *Trans. Geol. Soc. Glasgow*, XV (1913), 64–83, pls. 2.

Geological description of the upland region on the shore of the Firth of Clyde near Ayr. The hills consist of a series of lava flows of Old Red Sandstone age, and are composed of extrusive andesites and basalts and intrusive dolerites and *plagiophyres*, the latter term applied to plagioclase rocks analogous to the orthoclase-bearing *orthophyres*.

TYRRELL, G. W. "The Petrology of Arran," *Geol. Mag.*, X (1913), 305–9.

Riebeckite-orthophyre or riebeckite-trachyte is described from the Holy Isle, near Arran, and crinanites or olivine-analcite-dolerites, from Whiting Bay and Dippin.

TYRRELL, G. W., FERGUSON, D., and GREGORY, J. W. "The Geology of South Georgia," *Geol. Mag.*, I (1914), 53–64.

A description of the general geology of the island of South Georgia, 900 miles southeast of the Falkland Islands. The only igneous rocks found were certain crystal tuffs of andesitic, latitic, and trachytic character, an intrusive diabase or ophitic gabbro, and a quartz-monzonite-porphyry, the latter a fragment picked up from a moraine.

TYRRELL, G. W. "The Petrology of South Georgia," *Trans. Roy. Soc. Edinburgh*, L (Part iv), No. 25, 1915, 823–36, pl. 1.

This is a detailed petrographic description of the sediments and igneous rocks mentioned in the above paper. The rock previously determined as quartz-monzonite-porphyry is here called granite-porphyry.

USSING, N. V. "Geology of the Country around Julianehaab, Greenland." *Meddelelser om Grönland*, XXXVIII (1911). Pp. 370, figs. 28, maps and secs. 6, pls. 12, chemical analyses.

The southern third of Greenland is extremely poor in sedimentary rocks, only two small areas of post-Archean sediments being found in addition to certain Quaternary loam, sand, and gravel deposits. By a comparison with the sediments of northeast Canada, however, the order of succession of the various rocks may be inferred: Archean gneisses and schists, Algonkian(?) granites, diorites, etc., Devonian plutonic

rocks and volcanic sheets, and Quaternary moraines and alluvium. The most widely distributed rock in this region is a hornblende-bearing biotite-granite. The Devonian sheets are trachydolerites and alkali-trachyte. The later abyssal rocks are granites, syenites, nephelite-syenites, gabbros, and essexites, and of these all but the gabbros and essexites, which form small bosses, occur as batholiths. The nephelite-syenites are represented by lujavrites and other rare types, several of which have been given new names.

Naujaite is a sodalite-syenite, but since the latter term was used for rocks of quite different characters by Steenstrup, Lindgren, and Hibsch, the new name is proposed for a nephelite-syenite rich in sodalite, and having a peculiar poikilitic texture. The mode, computed from the chemical analysis and compared with the thin section, gives for two different specimens: sodalite 31 (54), nephelite 18 (5), eudialyte 3 (2), microcline 20 (6), albite 10 (—), ainigmatite —(2), aegirite 10 (12), arfvedsonite 1 (5), analcite 7 (14).

Sodalitite is almost exclusively made up of sodalite with very small amounts of aegirite, feldspar, and eudialyte.

Kakortokite is a coarse grained, trachytoid (foyaitic) nephelite-syenite. It differs from ordinary foyaite in its high percentage of dark constituents. Three varieties are described: black, white, and red. The minerals are eudialyte, alkali-feldspar, nephelite, arfvedsonite, and aegirite. Sodalite, ainigmatite, biotite, rinkite, fluorite, and epistolite, as well as zeolites, may be present. The chief minerals in the black rock are aegirite and arfvedsonite. They are present in about equal amounts and, while very abundant in other cases, make up 65 per cent of the black rock. The chief mineral of the white rock is microline-microperthite, the chief mineral of the red, eudialyte.

Agpaite is a general name given to the rocks occurring at Ilimausak, and includes the sodalite-foyaite, naujaite, lujavrite, and kakortokite.

VALETON, J. J. P. "Kristallform und Löslichkeit." *Ber. math-phys. Kl. kön. sächs. Gesell. Wiss.*, Leipzig. LXVII (1915), No. 78, pp. 59, figs. 10, pl. 1.

Determines that there is no difference in the solubility of alum in different directions. The laws of growth and solution must be explained on different grounds than solubility differences.

VAN ORSTRAND, C. E., and WRIGHT, FRED. E. "The Calculation and Comparison of Mineral Analyses," *Jour. Wash. Acad. Sci.*, IV (1914), 514–25.

Various methods for adjusting chemical analyses are discussed, and the conclusion is reached that the present method of direct comparison of weight percentages of chemical analyses is sufficiently accurate.

VISCONT, K. *On the Fluidal Texture of Some Dike Rocks from the Neighborhood of the Granite Stock of Turgojak in the Slatoust Mining District of the Ural Mountains.* 1913. Pp. 14. (In Russian language.)

The granite intrusion of Turgojak cuts metamorphosed Paleozoic schists. Both the granite body and the country rocks are cut by two series of dikes following tectonic lines.

WADA, T., Editor. *Beiträge zur Mineralogie von Japan*, No. 5, Tokyo, 1915. Pp. 201–5, numerous figures.

Contains miscellaneous mineralogical papers by K. Jimbo, N. Fukuchi, M. Suzuki, W. Watanabe, M. Kawamura, K. Nakashima, and others.

WARREN, CHARLES H. "The Ilmenite Rocks near St. Urbain, Quebec," *Amer. Jour. Sci.*, XXXIII (1912), 263–77, fig. 1.

The writer describes a rutile-ilmenite rock from St. Urbain, Quebec, which he proposes to call *urbainite*. Two specimens give rutile 20.4 (11.3), ilmenite-hematite 73.2 (84.5), sapphirine 3.2 (0.7), remainder 3.2 (3.2).

WARREN, CHARLES H. "Petrology of the Alkali-Granites and Porphyries of Quincy and the Blue Hills, Mass., U.S.A.," *Proc. Amer. Acad. Arts and Sci.*, XLIX (1913), 203–330, pls. 2, sketch maps 2, chemical analyses.

The alkaline granitic magma of Quincy and the Blue Hills is believed by the author to have been intruded by stoping after Middle Cambrian but before late Carboniferous times. Having nearly reached the surface, the upper portions are rather vitreous while lower portions are more crystalline and appear as granite-porphyries. Still lower the rock is a fine-grained granite. In one portion of the field the marginal phase is

broken up and intruded by later material. Locally there is a more basic phase where the magma differentiated against the slate or even under its own cover, and the rock is rhombic porphyry. No complementary dikes occur in the region.

WARREN, CHARLES H. "A Quantitative Study of Certain Perthitic Feldspars," *Proc. Amer. Acad. Arts and Sci.*, LI (1915), 127–54, fig. 1.

Micrometric readings and calculations from analyses of eight perthites show microcline 52.3–86.2 to albite 47.7–13.8 per cent by weight. The author comes to the conclusion held by Vogt, that perthitic structure in primary potassic feldspar, where the amount of albite is less than *ca.* 28 per cent, is due to the unmixing of previously homogeneous mixed crystals.

WARREN, CHARLES H., and POWERS, SIDNEY. "Geology of the Diamond Hill–Cumberland District in Rhode Island–Massachusetts," *Bull. Geol. Soc. Amer.*, XXV (1915), 435–76, figs. 3.

Gives a geological history of the region, and describes gabbro, cumberlandite, serpentine, labradorite-porphyry, quartz-diorite, granite, riebeckite-aegirite-granite, felsite, and various porphyries.

WASHINGTON, HENRY S. "The Volcanic Cycles in Sardinia." *Cong. géol. internat.* Canada, 1913. Pp. 11.

A preliminary statement of some of the general petrological relationships of the igneous rocks of Sardinia, and the bearing of these on certain phases of magmatic differentiation.

WASHINGTON, HENRY S., and LARSEN, E. S. "Magnetite basalt from North Park, Colorado," *Jour. Wash. Acad. Sci.*, III (1913), 449–52, analysis.

A brief description of a peculiar basalt from Colorado which contains 55 per cent of iron ore. It is the only known example of extruded lava so high in iron.

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—Ashley, G. H. Notes on the Greensand Deposits of the Eastern United States. Methods of Analysis of Greensand, by W. B. Hicks and R. K. Bailey. [U.S. Geological Survey, Bulletin 660-B. Washington, 1917.]

—Bailey, E. B., and Maufe, H. B., The Geology of Ben Nevis and Glen Coe, and the Surrounding Country. (Explanation of Sheet 53.) 53, Memoirs of the Geological Survey, Scotland. [Edinburgh, 1916.]

—Bastin, E. S., and Hill, J. M., Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado. [U.S. Geological Survey, Prof. Paper 94. Washington, 1917.]

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